WASHINGTON STATE DEPARTMENT OF ECOLOGY

Wenatchee National Forest Water Temperature Total Maximum Daily Load

Technical Report

Draft

June 2003
Publication Number 03-10-063

Printed on Recycled Paper

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Introduction

Total Maximum Daily Load Background

Section 303(d) of the federal Clean Water Act requires that states establish Total Maximum Daily Loads (TMDLs) for surface waters that do not meet water quality standards following the application of technology-based pollution controls. The U.S. Environmental Protection Agency (EPA) has promulgated regulations (40 CFR 130) and developed guidance (EPA, 1991) for establishing TMDLs.

Under the Clean Water Act, each state has water quality standards designed to protect, restore, and preserve water quality. Water quality standards are usually in the form of numeric criteria established to achieve beneficial uses, such as protection of cold water biota or drinking water supplies. When a lake, river, or stream fails to meet water quality standards after application of required technology-based controls, the Clean Water Act requires the state to place it on a list of "impaired" water bodies (known as the “303(d) list”) and to prepare an analysis called a **Total Maximum Daily Load (TMDL)**.

The goal of a TMDL is to ensure the impaired water will attain water quality standards. A TMDL includes a quantitative assessment of the extent of the water quality problem(s) and the pollutant sources causing the problem. The TMDL determines the amount of a given pollutant that can be discharged to the water body and still meet standards, the **loading capacity**, and allocates that load among the various sources. If the pollutant comes from a discrete source (referred to as a point source) such as an industrial facility’s discharge pipe, that facility’s share of the loading capacity is called a **wasteload allocation**. If it comes from a diffuse source (referred to as a nonpoint source) such as a farm, that facility’s share is called a **load allocation**.

The TMDL assessment must also consider **seasonal variations** in pollutant levels and include a **margin of safety** that takes into account uncertainty about the causes of the water quality problem or its loading capacity. The sum of the individual allocations and the margin of safety must be equal to or less than the loading capacity.

Wenatchee National Forest TMDL

This TMDL is being established for the pollutant, heat (solar radiation). Excessive heat loads to surface waters within Wenatchee National Forest have resulted in water temperatures exceeding the state water quality standard. Washington State’s water temperature standard that applies to surface waters within the Wenatchee National Forest (which are classified as AA) is that the maximum temperature remain below 60.8 degrees Fahrenheit (^{o}F) (16 degrees Celsius (^{o}C)).

Washington State’s 1998 303(d) list contains 18 individual water bodies within the Wenatchee National Forest where water temperature has been observed exceeding the temperature standard. More recent data, collected by the United States Forest Service (USFS) in 2001, indicates that there are an additional 46 locations with temperature exceedances.

While a TMDL that solely addresses the impaired (listed and unlisted) stream segments could be completed, due to the large amount of data that are available for the greater Wenatchee National Forest, it is more efficient and relevant to develop the analysis to address water temperature in perennial streams throughout the forest. For this reason, this TMDL uses broader resource functions and conditions to develop appropriate allocations across a diversity of local stream conditions and functions. With this approach, the TMDL allocations that result will help guide better protection of existing conditions to prevent future impairments.

TMDL Report Elements

The five elements of this TMDL, required by federal regulation and statute, are summarized below:

Loading Capacity: The loading capacity for heat (or solar radiation) is based on achieving effective shade levels in the riparian corridor needed to meet state water quality standards for temperature. Using a stream channel classification system that incorporates information - for instance, on geologic setting, drainage area, active channel width, and flow, effective shade - targets were developed. (Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface.) The classification system recognized the variability in channel and riparian characteristics that occur across the landscape and grouped streams that shared common water temperature influences such as shade, groundwater, or channel morphology.

Load Allocations: Allocations in this TMDL are based on percent effective shade and apply only to surface waters within the Wenatchee National Forest. Effective shade can be linked to source areas and, thus to actions (specifically riparian management) needed to address processes which influence water temperature.

Wasteload Allocation: There are no permitted discharges within the area covered by the TMDL therefore, the wasteload allocation is zero.

Margin of Safety: The margin of safety was determined to be the difference between the load allocation, or percent effective shade required to meet the temperature water quality standard, and the load capacity, represented by the effective shade generated by the natural potential vegetation. In addition, the analysis was based on data collected during critical conditions. The summer of 2001 was unusually hot and dry.

Seasonal Variation: Existing conditions for stream temperatures in the Wenatchee National Forest reflect seasonal variation. The warmest water temperatures typically occur between mid-July and mid-August. This time frame was used as the critical period for the development and analysis of allocations.

Surrogate Measures – Effective Shade

This TMDL assessment uses riparian shade as a surrogate measure of heat flux to fulfill the requirements of Section 303 part (d) of the Clean Water Act. Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface.

Heat loads to streams were calculated in this TMDL through the use of a numeric model (in units of calories per square centimeter per day or $cal/cm^2/day$). However, heat loads are of less relevance in guiding management activities needed to solve identified water quality problems. For this reason, shade is used as a surrogate to the thermal load as allowed under EPA regulations (defined as “other appropriate measure” in 40 CFR §130.2(i)).

Overview of Heating Processes

While climate and geographic location are outside of human control, riparian condition, channel morphology, and hydrology are affected by land use activities. The following processes affect water temperatures in the Wenatchee National Forest:

- Riparian vegetation disturbance reduces stream surface shading via decreased riparian vegetation height, width, and/or density, thus increasing the amount of solar radiation reaching the stream surface.
- Channel widening (increased width to depth ratios) increases the stream surface area exposed to energy processes, namely solar radiation.
- Reduced summertime base flows may result from in-stream withdrawals and hydraulically connected groundwater withdrawals. Reducing the amount of water in a stream can increase stream temperature.

A decrease in shade, due to low riparian vegetation levels, causes an increase in absorbed solar radiation to the stream surface. Activities that contribute to reduced riparian shade include livestock grazing, recreation, agriculture, and logging. Figure 1 provides the major pathways that allow excessive solar radiation to reach a stream and are among the factors considered in this analysis.

The amount of solar radiation that reaches a stream surface is a primary factor in the maximum water temperature that is realized (figure 1, 1). The amount of the solar load delivered to a stream is in turn determined by two pathways, a vegetation-related component (2) and the other sediment-related (3). Effective shade is determined primarily by the height and density of riparian vegetation (4). The width-to-depth ratio determines the potential stream surface area exposed to solar radiation and is determined by the amount of sediment within the channel (5). The amount of sediment delivered to a stream is a function of the erosion-related activities present within a particular drainage area such as existing roads (and those under construction), and hillslope failures (7). Excessive delivery of sediment to channels can also affect riparian vegetation through compensating channel morphological changes that result in streambank failure (6).

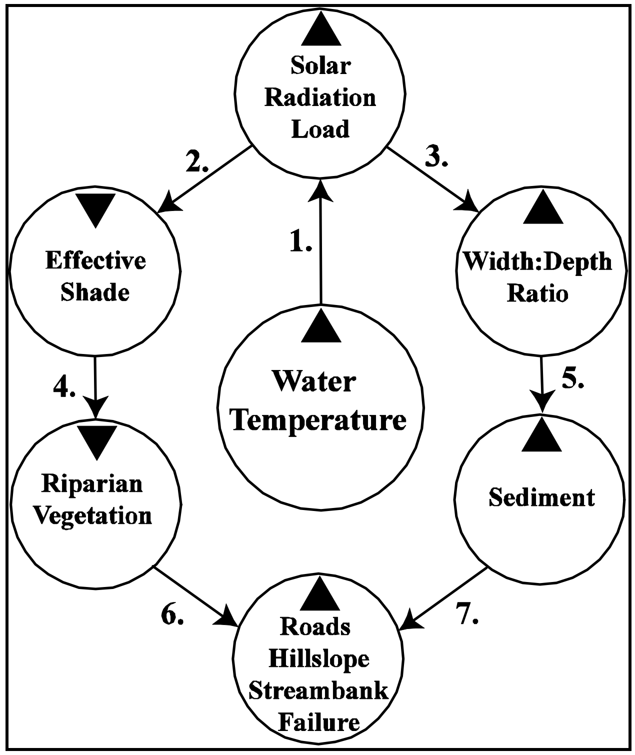

Figure 1. Shade and channel characteristics and their effects on water temperature.

Heat Budget - Framework for Linking Water Temperature and Shade

Water temperature is related to the heat content of water but is actually a measure of the intensity or concentration of stored heat within a given volume. Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature and, therefore, the heat flux. For this reason, in order to understand the changes in temperature of water, a budget, or an accounting of the major gains and losses of heat must be considered.

The heat budget expresses this in mathematical form:

$$J_{net} = J_{longwave} + J_{solar} + J_{convection} + J_{evaporation} + J_{bed} + J_{hyporheic} + J_{in\ (surface\ or\ ground)} + J_{out}$$

"J" represents the flux of each component, which can be positive or negative (units in calories per square centimeter per day). Objects emit absorbed heat in the form of long-wave radiation ($J_{longwave}$)(figure 2, 1). The atmosphere provides some long-wave radiation to water bodies, but more tends to be emitted by the water bodies, generally resulting in a net loss of heat. Solar, or short-wave radiation, (J_{solar}) tends to dominate the heat budget where effective shade is low (2). Solar radiation inputs peak at mid-day and do not occur at night. Important, in terms of this TMDL, is that the solar shortwave flux to a stream can be controlled (depending on the stream width and vegetation growing conditions) by managing riparian vegetation. Riparian vegetation blocks the total potential short-wave radiation load from entering the stream, limiting potential temperature increases. This is the reason why the percent effective shade, or the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface, is used as the principal management parameter in this TMDL.

Heat can be transferred through convection ($J_{convection}$) (3). If a stream is hotter than the air temperature above it, heat is transferred from the stream to the air, resulting in a decreased water temperature. Wind transfers heat horizontally, dissipating air temperature gains next to the stream surface. This process maintains a temperature gradient, driving convection losses from the stream. If air temperature exceeds water temperature, heat is transferred into the stream. However, this term tends to be small relative to other heat fluxes.

Evaporation ($J_{evaporation}$) results in a transfer of latent heat from the water body to the air, although it is small relative to other terms in the heat budget equation (4). Finally, heat can be transferred to or from the bed through advective exchange of water containing heat ($J_{hyporheic}$) or by conduction (J_{bed}) with the sediments (Beschta et al., 1987) (5). In addition, heat is advected in (J_{in}) and out (J_{out}) of a reach via surface water transport. As it will be discussed later in this report, groundwater inflow can have a significant cooling effect on stream temperature during warm summer months. Subsurface flow, surface water inflow, and rain are the primary advective sources. The role of advection depends on the volume of groundwater or tributary inputs relative to the total stream discharge, for this reason, the influence of groundwater cooling diminishes in a downstream direction.

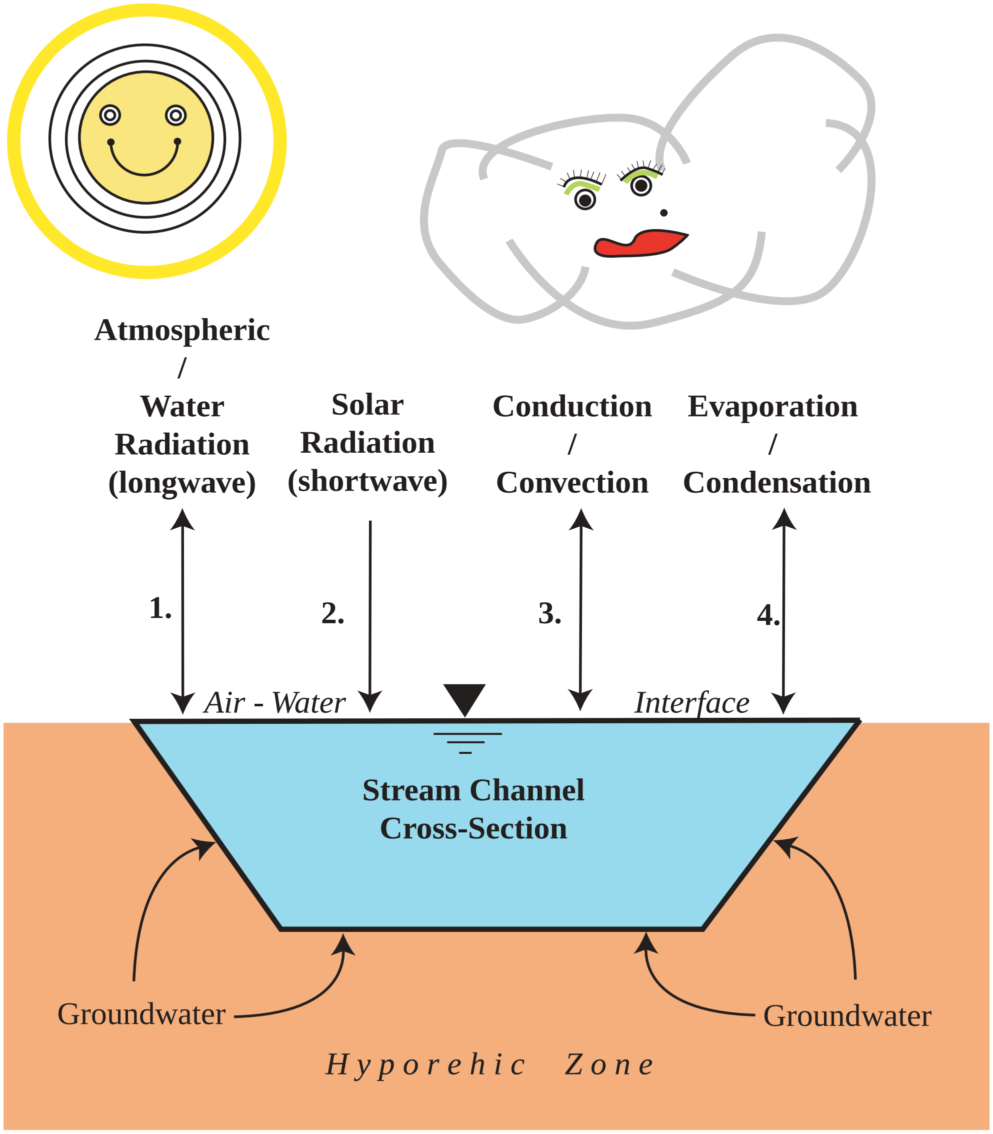

Figure 2. The heat energy processes that effect water temperature.

Heat Equation

A loading capacity for heat (expressed as BTU/ft2 per day) can be derived using an analysis of heat transfer processes in water. One of the most basic forms of a heat transfer analysis is the fundamental equation applied by Brown (1969) for forest streams .

$$\Delta T = (\Delta H * A) / (V * \rho * c_p)$$

ΔT	Temperature change (°F / hour)
ΔH	Rate that heat is received (BTU / hour)
A	Surface area (ft^2)
V	Volume (ft^3)
ρ	Density of water (62.4 lb / ft^3)
c_p	Specific heat of water (BTU/ lb / °F)

The calculation of water temperature by a mechanistic model follows the basic relationship described by the equation above. A mechanistic model is essentially a bookkeeping of different heat transfer processes to determine potential water temperature changes.

The change in water temperature follows the change in heat received, as described by the relationship. The analysis is essentially a bookkeeping of heat transfer, also known as a heat budget, to determine potential water temperature changes. The heat budget technique utilizes six variables (solar radiation, long wave radiation, evaporation, convection, bed conduction, and advection) to determine the net gain or loss of stored heat (ΔH) in a known volume of water. The change in ΔH is then converted to a water temperature change.

An advantage of the heat budget approach is that it goes beyond a narrow focus on maximum water temperatures. Maximum water temperatures simply reflect symptoms when criteria values are exceeded. Because the TMDL is designed to decrease the pollutant load during a critical time frame, the analysis of heat transfer processes allows a more direct assessment of causes. The daily profile for water temperature increases typically follows the same pattern of solar radiation delivered to an un-shaded stream. Thus, two critical time frames for development of loading capacity targets are the period of the day when the solar radiation flux has the greatest potential to deliver large quantities of heat energy to the stream and the diurnal range.

Stream Channel Characteristics

One drawback to the use of a heat budget or any mechanistic model, however, is the difficulty in determining solar radiation loads over each stream mile of a large watershed. The curves that result from numerical calculations (stream heat exchange processes) are influenced by a number of factors including stream flow, channel width, upstream water temperature, wind speed, relative humidity, stream bed composition, and groundwater contribution. As observed by the equation presented above, the temperature change produced by a given amount of heat is inversely proportional to the volume of water heated (stream discharge).

Also, the amount of heat that is gained (or lost) and the rate at which exchange takes place, depends on the surface area of the stream. Wide, shallow streams exhibit greater radiative, convective and evaporative exchange and, consequently, heat and cool more rapidly than deep narrow streams. Similarly, the rate of energy exchange is affected by seasonal changes in stream discharge which alter surface to volume ratios and determine the relative importance of groundwater inputs.

Background

Description of Study Area

The 3480 square mile Wenatchee National Forest is located on the east slope of the Cascade Range in central Washington State. The dimensions of the forest from north to south are approximately 140 miles and range between 30 to 50 miles east to west. Five river basins are found within the forest, oriented from north to south, they include: the Chelan (17% of forest area), Entiat (11%), Wenatchee (33%), Yakima (18%), and Naches (22%).

The crests of the Cascade Mountains form much of the forest's western boundary while to its eastern edge is the Columbia River. Between the two, elevations range from approximately 9000 feet within the common ice fields of the upper Entiat and Chelan basins (Mount Stuart, within the Wenatchee basin, has a peak elevation of approximately 9400 feet) to approximately 1500 feet in lower Entiat, Wenatchee, and Chelan basins, near the Columbia River.

Corresponding with these elevation extremes are similar levels of change in precipitation. The upper elevations of the Cascade Range have annual precipitation levels of approximately 130 inches (most falling as snow from November to February) to approximately 10 inches near the Columbia River. The west-to-east transition from maritime to semi-desert conditions is the result of a rain-shadow effect of the Cascade Range. With prevailing winter storms from the Pacific Ocean approaching the Cascades from the southwest, the majority of the precipitation associated with storm events falls to the west and at the mountain crests. This rain-shadow affect results in large variations in the type and distribution of vegetation within the forest. A mountain hemlock and silver fir environment occurs within the moist maritime conditions along the slopes of the Cascades while a shrub-steppe environment is present in the lower elevations of the Entiat and Wenatchee basins (Lillybridge, 1995).

Statement of Problem

Chronically elevated water temperatures have been observed at numerous locations throughout the Wenatchee National Forest based on data collected since 1995 by the USFS. Washington State's water quality standard for temperature that applies to surface waters within the Wenatchee National Forest (which are classified as AA) is that the maximum water temperature should remain below 60.8^{o}F (16^{o}C). Much of the USFS water temperature data, along with additional data submitted by the Yakama Indian Nation, has been used by the Washington State Department of Ecology to include 18 separate water bodies within the forest on the state's 1998 303(d) list of impaired waters (**http://www.ecy.wa.gov/programs/wq/303d/1998/1998_by_wrias.html**) (figure 3). In addition, data collected by the USFS as part of routine temperature monitoring at 137 stations in 2001 indicates that a further 46 water bodies are impaired, as indicated by maximum water temperatures exceeding the standard.

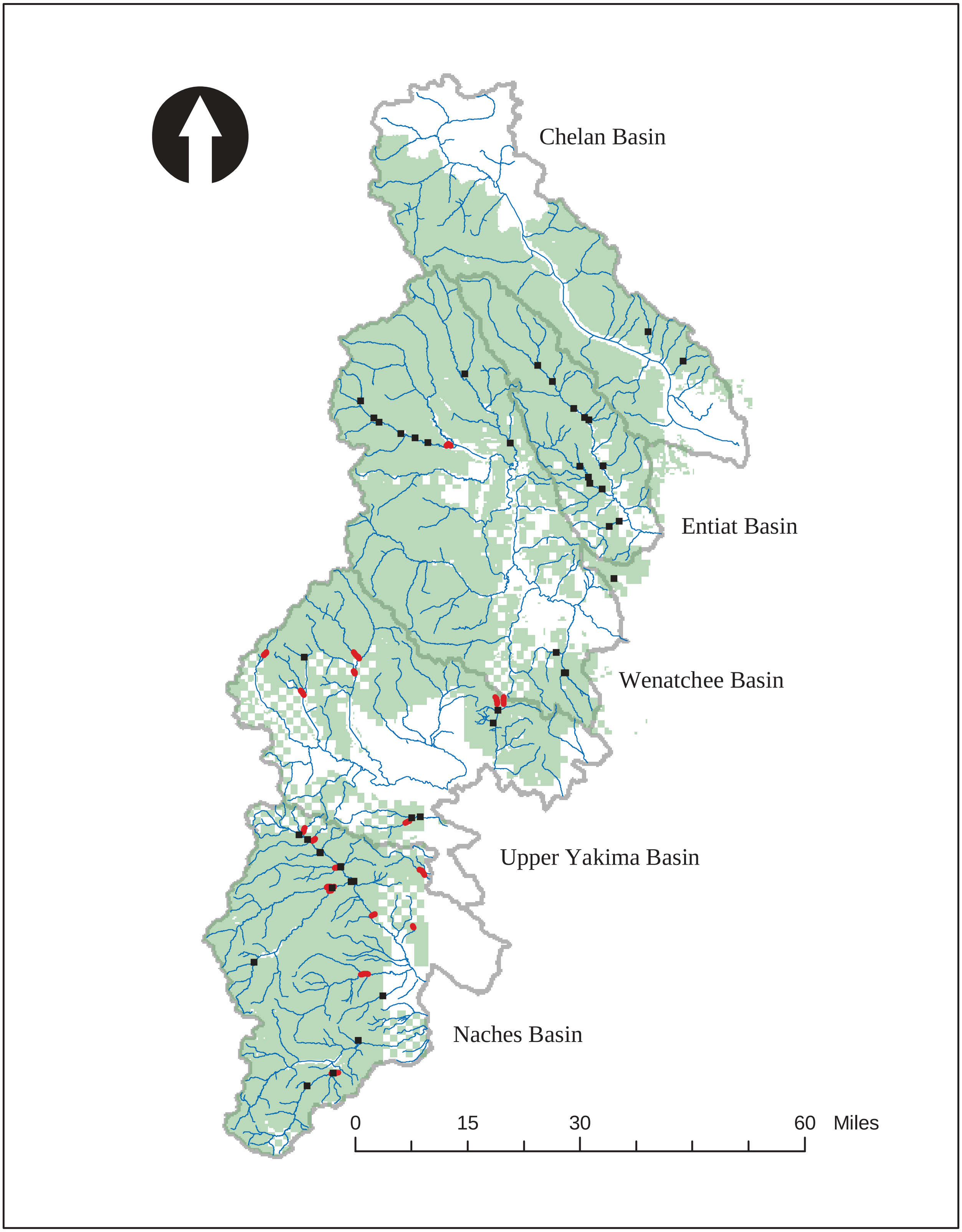

Figure 3. Listed (red) and impaired (black) surface waters within the Wenatchee National Forest.

Applicable Criteria

This TMDL analysis is designed to address impairments of characteristic uses caused by elevated water temperatures. The water quality standards, set forth in Chapter 173-201A of the Washington Administrative Code (WAC), include designated beneficial uses, classifications, numeric criteria, and narrative standards for surface waters of the state. The characteristic uses designated for protection in the Wenatchee National Forest are as follows (Chapter 173-201A WAC):

"Characteristic uses. Characteristic uses shall include, but not be limited to, the following:
(i) Water supply (domestic, industrial, agricultural).
(ii) Stock watering.
(iii) Fish and shellfish:
Salmonid migration, rearing, spawning, and harvesting.
Other fish migration, rearing, spawning, and harvesting.
Clam and mussel rearing, spawning, and harvesting.
Crayfish rearing, spawning, and harvesting.
(iv) Wildlife habitat.
(v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).
(vi) Commerce and navigation."

The state water quality standards describe criteria for temperature for the protection of characteristic uses. Streams in the Wenatchee National Forest are designated as Class AA. The temperature criteria for Class AA waters are as follows:

> "Temperature shall not exceed 16.0°C…due to human activities. When natural conditions exceed 16.0°C…, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

During critical periods, natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. In these cases, the anti-degradation provisions of those standards apply.

> *"Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."*

Water Quality and Resource Impairments

Water bodies located within the Wenatchee National Forest that are included on Washington State's most current (1998) 303(d) list for temperature are included in table 1. The water temperature of many of these 18 streams was monitored in 2001 as part of a USFS expanded monitoring effort. That data indicates that the majority of these sites continue to experience maximum water temperatures exceeding the standard.

Table 1. Water bodies within the Wenatchee National Forest included on the 1996 and 1998 303(d) lists for water temperature.

Water Body	Subsection	WRIA	1996 WBID	1998 WBID	Township, Range, Section	1996 List	1998 List
Cooper R.	Co	39	WA-39-1055	WX84IT	22N,14E,16	X	X
Gale Ck.	Co	39	WA-39-1300	RZ54RL	22N,13E,32	X	X
Gold Ck.	Co	39	WA-39-1390	ZS28LG	22N,11E,01	X	X
Iron Ck.	Cn	39	WA-39-1440	YW62RW	21N,17E,03	X	X
SF Manastash Ck.	Cc	39	WA-39-3025	WW44PW	18N,15E,36	X	X
SF Taneum Ck.	Co	39	WA-39-1570	WJ69FI	19N,15E,27	X	X
Waptus R.	Co	39	WA-39-1057	XB92PJ	22N,14E,04	X	X
Blue Ck.	Cn	39	WA-39-1435	BU07PV	21N,17E,02	X	X
American R.	Cp	38	WA-38-1060	QX86IU	17N,13E,12	X	X
Bear Ck.	Cp	38	WA-38-1088	JJ42VM	19N,13E,32	X	X
NF Nile Ck.	Cc	38	WA-38-2110	IN37QB	16N,15E,03	X	X
Bumping R.	Cp	38	WA-38-1070	XR40PP	17N,13E,12	X	X
Crow Ck.	Cp	38	WA-38-1081	TL45HC	18N,14E,30	X	X
Gold Ck.	Cp	38	WA-38-1041	CR82VL	17N,14E,36	X	X
Mathew Ck.	Cp	38	WA-38-1086	LW85BJ	18N,13E,10	X	X
SF Tieton R.	Cp	38	WA-38-3000	NV27KW	13N,13E,13	X	X
Rattlesnake Ck.	Cp	38	WA-38-1035	MB08QY	15N,14E,10	X	X
Little Wenatchee R.	Ca	45	WA-45-4000	DS66LF	27N,16E,15	X	X

Based on the 2001 water temperature monitoring data from 137 locations throughout the forest, an additional 46 sites had maximum water temperatures that exceeded 60.8 ^{o}F (16 ^{o}C), the state temperature standard. At many of these sites, water temperatures were chronically elevated throughout the summer. These impaired sites are listed in table 2**.**

Table 2. *Water bodies where water temperatures were observed at levels exceeding the 60.8°F water quality standard in 2001.*

Water Body	Stream Name	WRIA	Subsection	Township, Range, Section	2001 Annual Max
HAUS_01	Hause Ck.	38	Cp	14N, 14E, 21	64.4
SFTI_01	South Fork Tieton	38	Cp	13N, 13E, 13	65.0
LTRA_02	Little Rattlesnake Ck.	38	Cp	15N, 14E, 25	63.8
LTNA_01	Little Naches R.	38	Cp	17N, 14E, 4	69.8
LTNA_02	Little Naches R.	38	Cp	18N, 14E, 30	68.7
LTNA_04	Little Naches R.	38	Cp	18N, 13E, 14	67.0
LTNA_05	Little Naches R.	38	Cp	18N, 13E, 9	64.9
LTNA_06	Little Naches R.	38	Cp	18N, 13E, 5	64.8
SANDN_01	Sand Ck.	38	Cp	18N, 13E, 14	62.8
BUMP_01	Bumping R.	38	Cp	17N, 14E, 4	70.5
BUMP_03	Bumping R.	38	Cp	17N, 13E, 12	72.0
BUMP_06	Bumping R.	38	Cp	16N, 11E, 36	64.9
QUAR_01	Quartz Ck.	38	Cp	18N, 14E, 30	61.2
GREY_01	Grey Ck.	38	Cp	13N, 13E, 29	62.7
ENTI_12	Entiat R.	46	Cb	28N, 19E, 33	67.5
ENTI_13	Entiat R.	46	Cb	28N, 19E, 29	65.4
ENTI_14	Entiat	46	Cb	28N, 18E, 2	61.7
NFEN_01	North Fork Entiat	46	Cb	29N, 18E, 27	61.5
SWAKANE	Swakane Ck.	46	Cq	24N, 20E, 16	75.5
ROAR_01	Roaring Ck.	46	Cq	25N, 20E, 8	70.1
ROAR_02	Roaring Ck.	46	Cq	25N, 20E, 7	65.3
POTA_01	Potato Ck.	46	Cq	27N, 19E, 36	69.7
PRES_01	Preston Ck.	46	Cb	28N, 19E, 34	63.8
MITC_01	Mitchel Ck.	46	Cb	29N, 21E, 24	61.2
MADR_01	Mad R.	46	Cq	26N, 19E, 13	70.1
MADR_02	Mad R.	46	Cq	26N, 19E, 15	69.3
MADR_03	Mad R.	46	Cq	26N, 19E, 10	68.4
MADR_04	Mad R.	46	Cq	27N, 19E, 33	68.9
GRAD_02	Grade Ck.	47	Cb	30N, 21E, 31	61.0
LTWE_02	Little Wenatchee R.	45	Ca	27N, 16E, 18	68.1
LTWE_03	Little Wenatchee R.	45	Ca	27N, 15E, 11	65.5
LTWE_05	Little Wenatchee R.	45	Ca	27N, 15E, 10	65.9
LTWE_07	Little Wenatchee R.	45	Ca	28N, 14E, 36	64.7
LWTE_09	Little Wenatchee R.	45	Ca	28N, 13E, 14	62.6
LAKEW_01	Lake Ck.	45	Ca	28N, 15E, 31	64.8
CHWA_01	Chiwawa R.	45	Ca	27N, 18E, 30	64.0
CHWA_02	Chiwawa R.	45	Ca	27N, 17E, 13	64.9
ROCK_01	Rock Ck.	45	Ca	29N, 17E, 31	61.1
SANDW_01	Sand Ck.	45	Cm	22N, 18E, 1	64.3
EFMI_01	East Fork Mission	45	Cm	22N, 19E, 18	72.0
DEVI_01	Devils Gulch	45	Cm	22N, 19E, 18	68.9
IRON_01	Iron Ck.	39	Cn	21N, 17E, 10	64.1
MINE_01	Mineral Ck.	39	Co	22N, 13E, 5	66.2
BLUE_01	Blue Ck.	39	Cn	21N, 17E, 22	63.0
TANE_01	Taneum Ck.	39	Co	19N, 15E, 25	68.5
NFTA_01	North Fork Taneum Ck.	39	Co	19N, 15E, 26	63.4

Overview of Wenatchee National Forest Water Temperature Data

The goal of this TMDL is to establish forest-wide riparian shade levels (in terms of percent effective shade) to maintain maximum water temperatures at, or below, the water quality standard. An overview of the data used to make these determinations provides a useful foundation for explaining water temperature variability across the forest and some of the analysis considerations used to determine the load allocations.

In 2001, water temperature was measured at 137 locations distributed throughout the Wenatchee National Forest (figure 4). The monitoring sites covered a variety of channel types, drainage areas, geologic settings, elevations, and vegetative communities. (Additional information on each monitoring stations is included in Appendix B.) In some cases, surface waters outside of the forest were also monitored. Typically, these locations were part of a network of monitoring sites located on larger river systems. (A larger network of temperature probes was deployed on the Entiat, Chiwawa, Little Wenatchee, and Naches Rivers as part of the thermal infrared remote sensing conducted in August of 2001.)

For most of the monitoring sites, water temperatures were recorded every 30-minutes from June though September, bracketing the period when the most elevated water temperatures occur. In 2001, the majority of the stations recorded peak water temperatures on August 12. For this reason and to provide a common information base, the observations presented in this section are based on data collected on that day.

The elevations where monitoring stations were located ranged between 782 feet (msl) at the Entiat River station 1, to 4300 feet at the Mad River station 7. The median elevation for the monitoring stations was 2504 feet. The median drainage area above the monitoring locations was 22 square miles but ranged between 1 and 418 square miles.

Minimum and maximum water temperatures

For the majority of the monitoring stations, there is some commonality in the relationship between the minimum and maximum water temperature recorded on August 12 (figure 5). As observed, streams with lower maximum water temperatures also tended to have lower minimums whereas those that have the most elevated daily maximums also had corresponding elevated minimums.

Streams with the coldest maximum water temperatures (and minimums) tend to be those that have greater groundwater inflow comprising the majority of their flow, typified by the higher elevation first and second order streams. (The temperature of groundwater within the greater Wenatchee National Forest is approximately 50^{o}F (10 ^{o}C).) For those streams that experience the upper temperature extreme, a greater variety of influences are likely present among them: low riparian shade levels, low groundwater inflow in relation to the total stream flow, storage (thermally stratified inflow from lakes and reservoirs), and flow diversion.

Based on the relationship between minimum and maximum water temperatures, the minimum water temperature typically observed for those stations that remained at or below the water

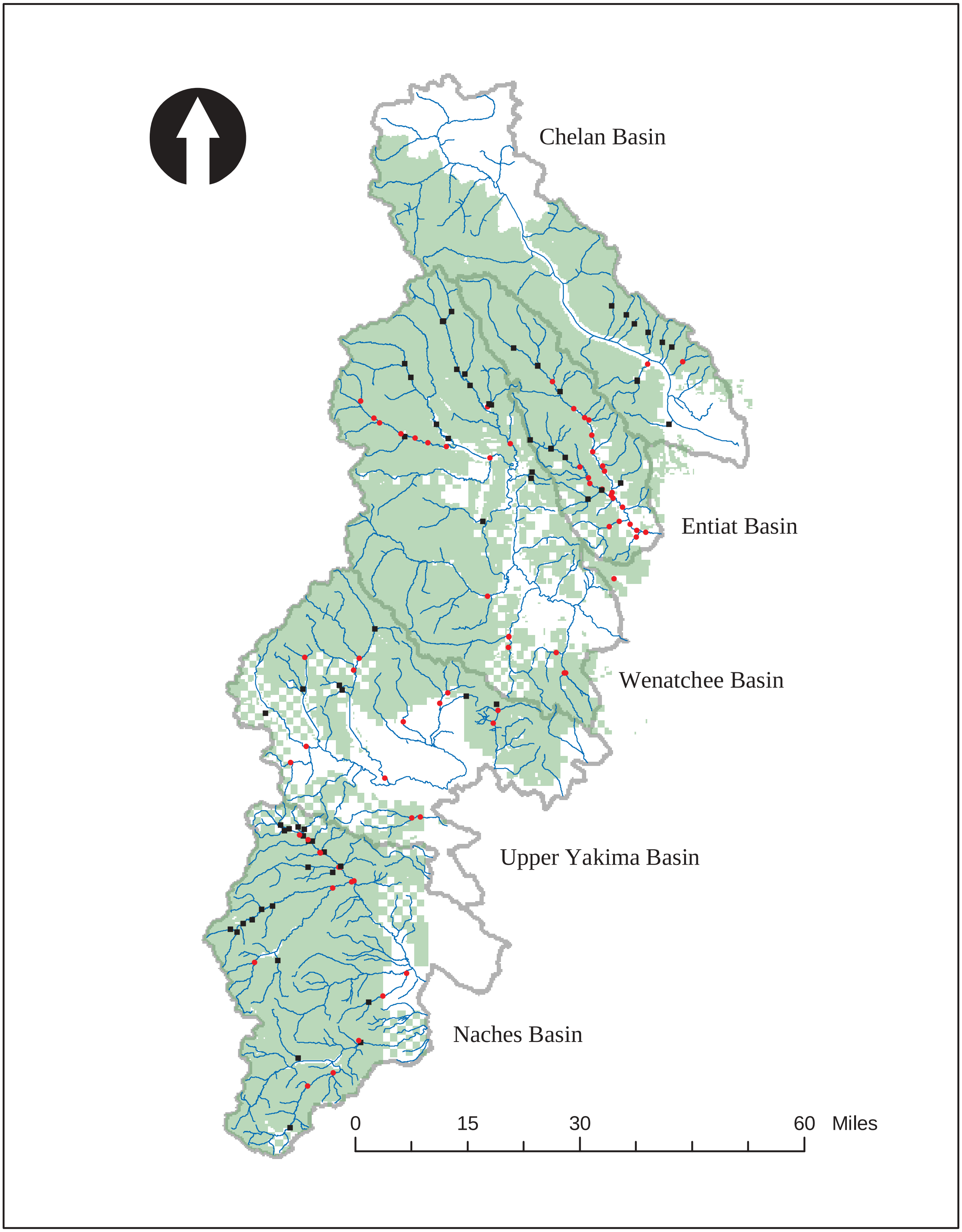

Figure 4. 2001 USFS water temperature monitoring locations. Stations with maximum temperatures above and below the standard are depicted in red and black, respectively.

temperature standard of 60.8°F (16°C) was approximately 53°F. Overall, median temperatures for the monitoring stations were a maximum of 61.2 °F, a minimum of 53.5 °F, and a diurnal range of 7.7 °F.

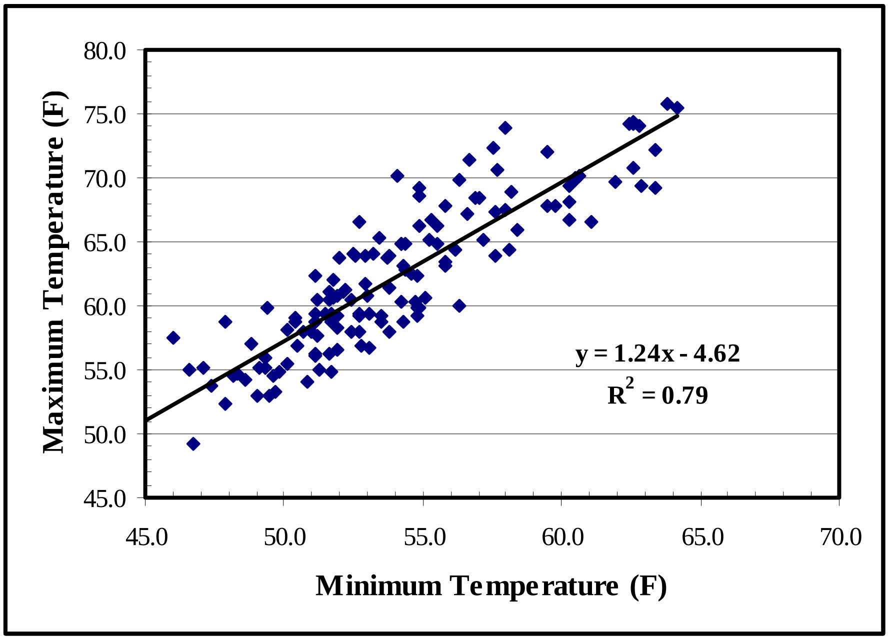

Figure 5. The relationship between the minimum and maximum water temperature observed on August 12, 2001 at the Wenatchee USFS monitoring stations.

<u>Diurnal Range</u>

Table 3 provides a statistical overview of the diurnal range (maximum minus minimum on August 12) observed for various ranges of maximum water temperature. As expected, the coldest maximum water temperature range, those within the 50 to 55°F range, have the lowest median diurnal temperature variation (approximately 5 °F). Again, these streams likely have groundwater discharge comprising the majority of the in-stream flow and are, therefore, buffered from wide variations in temperature. In contrast, for the upper ranges, 65°F+, the overall median temperature range is approximately 10°F. These streams experience chronically elevated water temperatures for a variety of reasons but the lack of riparian shade is likely a common one.

Table 3. Statistical overview of the diurnal range (°F) observed for several maximum water temperature ranges.

Maximum Temperature Range	N	Median Range	Max Range	Min Range	75th Percentile Range	25th Percentile Range	Temp. Max Median	Temp. Min Median
50 – 55	16	4.6	8.4	2.5	5.8	3.6	54.2	48.8
55 – 60	44	6.4	11.5	3.6	7.6	5.1	58.5	51.6
60 – 65	36	8.9	11.8	5.6	10.3	7.8	62.7	53.8
65 – 70	29	9.8	14.3	5.5	11.5	8.0	67.8	57.6
70 – 75	15	11.8	16.0	8.2	13.9	11.3	72.4	62.4

Excluding monitoring stations highly influenced by groundwater inflow (50-55 °F), the temperatures characteristics of stations where the maximum water temperature remained below the standard are represented by the range 55 – 60°F. Within this range the median maximum temperature was 58.5°F with a median diurnal range of 6.4°F. The 75th and 25th percentiles are 7.6 and 5.1°F, respectively. Based on these results, it can be extrapolated that for streams to achieve an annual maximum at the water quality standard (60.8° F) they should have a diurnal range of approximately 5 to 8 degrees resulting in a low of between 53 to 56 degrees on the day the maximum water temperature is observed.

While a significant relationship between the minimum and maximum water temperatures was observed for the monitoring stations, the diurnal range has a lower correlation with the maximum water temperature (figure 6).

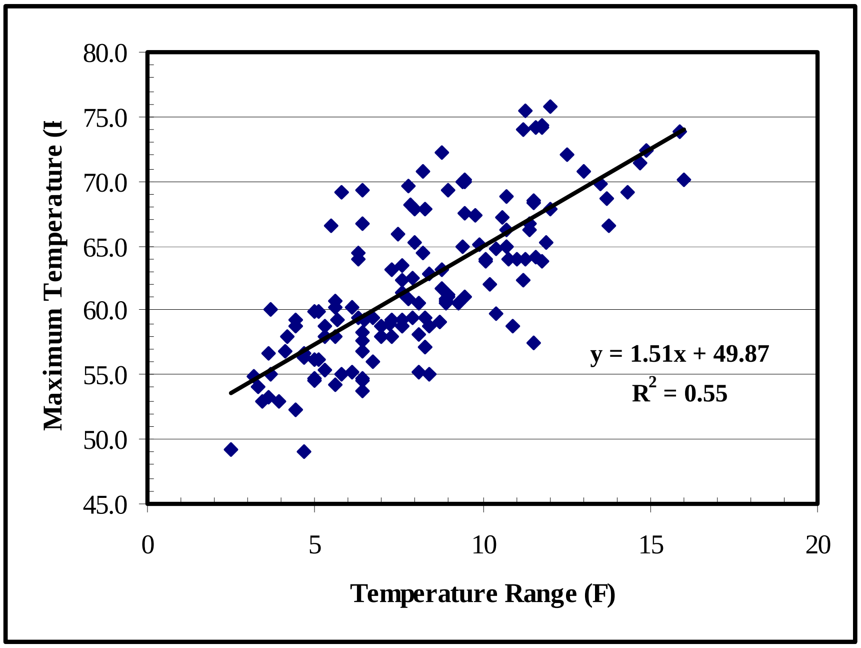

Figure 6. The relationship between the diurnal temperature range and the maximum water temperature observed on August 12, 2001 at the Wenatchee USFS monitoring stations.

The scatter in the relationship between the diurnal range and the maximum water temperature was examined closer to determine if there certain characteristics shared for those stations on the upper and lower extremes. These data outliers were divided into two groups depicted in figure 7 by the squares (warm-water stations) and diamonds (cold-water stations). As it can be observed, the warm-water stations all have a greater maximum water temperature in relation to their diurnal range when compared to the majority of the monitoring stations and the cold-water stations tend to have a colder maximum in relation to their diurnal range.

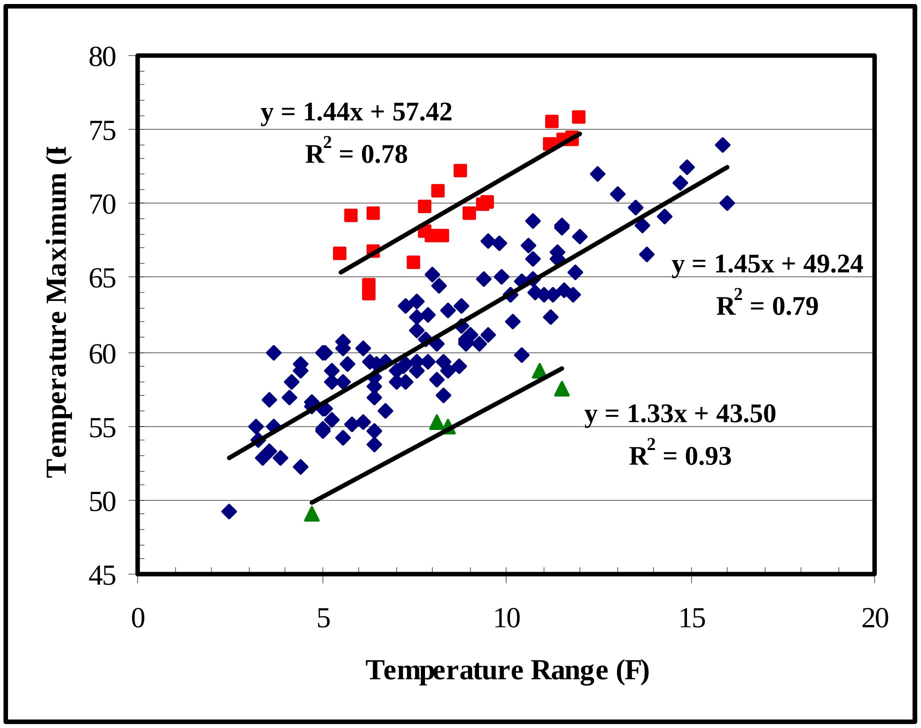

Figure 7. The relationship between the diurnal range (°F) and the maximum water temperature based on three subgroups: squares represent warm-water outliers and the triangles represent cold-water outliers in relation to the main dataset (diamonds).

Warm-water Stations

A common characteristic for many of the warm-water stations is having a significant amount of water storage in the form of natural lakes or impoundments that contribute to flow passing the monitoring locations. Included in this grouping are the monitoring stations located on Lake Creek (Little Wenatchee River), Yakima River, Cle Elum River, Cooper River, Waptus River, lower Bumping River, Little Wenatchee (below Lake Creek and at Wenatchee Lake), and Icicle Creek. The storage of heat within these impoundments has the effect of modifying water temperatures by maintaining more elevated minimum water temperatures at downstream locations. For this reason, streams that receive outflow from lakes or reservoirs experience higher minimum water temperatures and, with all other heating factors equal, will experience greater maximum water temperatures.

Also, included among the warm-water sites are Mad River stations (0 through 3), Entiat River (1 through 9), and Nason Creek. These stations follow the pattern observed for the monitoring stations with water storage though not sharing that characteristic within their drainages. Instead, these streams likely have greater storage of heat within their channels due to common characteristics like long flow paths (Entiat), flow through lower elevations with higher minimum air temperatures reducing the potential for night-time cooling through convection, storage within pools (Mad River), conductive heating from bedrock (Mad River), as well as low groundwater inflow and high exposure. Another common characteristic of the warm-water stations without storage is that they are situated in the lowest elevations among the monitoring stations. The average elevation for these stations is 1301 feet in comparison to the overall average of 2485 feet. In particular, the elevations of the Entiat River stations (1 through 9) are low with an overall average of 1092 feet, with a range from 782 feet at the lowest station (1) to 1462 feet (9). In a sense, elevation is a surrogate for many of the characteristics mentioned above. These warm-water stations at the lower elevations tend to be higher order streams with greater width to depth ratios (higher exposure), lower levels of effective shade, with groundwater inflow comprising a lower percentage of the total flow, reducing this potential source of cooling.

With limited heat buffering from groundwater inflow, low shade levels magnify the heating problem (Entiat and Mad) the minimum water temperatures remain elevated while the peak equilibrium temperatures are reached relatively quickly (73 to 75°F.)

<u>Cold-water Stations</u>

The cold-water stations are represented by Deep Creek (Naches), Indian Creek (Entiat), Phelps (Wenatchee), American River above the Rainier fork (Naches) and the South Fork Tieton at the 1070 crossing. The characteristic these stations share is that the maximum water temperature remains lower than expected (in comparison to the majority of the monitoring stations) given their respective diurnal range. In direct contrast to the warm-water monitoring stations (those without storage), these stations are situated in among the highest elevations of the monitoring sites. The average elevation for these sites is 3517 feet with a range between 2958 feet for Indian (Naches) to 3950 feet for the South Fork Tieton (3). (In comparison, the average elevation for all the monitoring stations is 2485 feet.) Given the high elevation, night-time cooling is significant. In fact, these stations had among the lowest minimum water temperatures of the monitoring sites, with an average minimum of 46.4°F. (In comparison, the average minimum for all of the monitoring stations was 54.1°F)

Again, elevation is a surrogate of other heating characteristics. In the case of the cold-water stations, the overwhelming influence on water temperature is groundwater. At all of these stations groundwater likely comprises the majority of the flow and, therefore, has a moderating influencing on the maximum water temperatures observed. For instance, the South Fork Tieton station (3) is located in Conrad Meadows with naturally low effective shade levels. Low shade levels result in this station having a diurnal range of approximately 11°F. For the majority of the stations, this large a temperature range would result in maximum water temperature of approximately 65°F, exceeding the water quality standard. However, a maximum temperature of only 58.8 °F was recorded.

The warm-water (those with storage) and cold-water sites are functioning in a similar way; both have a heat reservoir that has a moderating effect on the diurnal temperature range. The cold-water stations have groundwater serving as their heat reservoir (reducing heat) and the warm-water stations have lake or reservoir storage (supplying heat).

Despite differences between the three water temperature groups all have a similar rate of heating expressed by the slope of the regression lines depicted in figure 7. The average slope of the lines is 1.41, so for each 1°F increase in the diurnal range there is a corresponding 1.41°F increase in the maximum water temperature. The reason for this is intuitive in that all three grouping are exposed to the same heating processes. However, what distinguishes the groups are their respective y-intercepts. The intercepts, in a sense, represent the minimum water temperature. For the warm and cold-water stations the y-intercept is 57.4 and 43.5^{o}F, respectively, an approximately 14^{o}F spread. The majority of the stations fall right in between with a y-intercept of 49.2^{o}F. Based on the median diurnal range observed for stations meeting the water quality standard (7^{o}F) it can be extrapolated that the warm-water sites with storage will likely never meet the standard while the cold-water sites will likely always meet it despite widely varying shade levels.

Geology – The influence of elevation and groundwater on water temperature

Based on the previous discussion, it is apparent that there are landforms or areas within the forest where, due to geological characteristics, greater groundwater storage and supply occur resulting in colder water temperatures. The association between the monitoring sites that met the temperature standard and geologic setting was examined to identify situations where greater storage and discharge of groundwater are present.

Land-type associations (LTA), or areas that share common topographic, geologic, and potential natural vegetation characteristics were delineated for the Wenatchee National Forest (Davis, 2000). Integrated within the LTA is a qualitative assessment of the aquifer recharge potential associated with each land-type based on the depth and texture of the overburden (material residing above bedrock), landform shape, exposure, gradients, geologic fracturing and structure, annual precipitation, and surface drainage configurations. A high, moderate, and low recharge potential was associated with each of the 18 land-types identified for the forest. This information is particularly useful for determining, on a landscape basis, what surface waters have high groundwater discharge and, therefore, likely have colder water temperatures.

The association between land-type and monitoring stations where maximum water temperatures remained below the standard was examined. The results of this analysis identified certain land-types associated with colder streams, indicative of higher groundwater inflow. They include: scoured glaciated mountain slopes (G), glaciated mountain slopes (I), glacial troughs (K), glacial moraines (L), landslides (T), and moderately steep volcanic flows (X). All of these landforms have a high to moderate groundwater recharge potential associated with them. An additional land-type associated with colder water is scoured glacial troughs (F). While this land-type has a low recharge potential it is situated in the highest elevations of the landforms in the forest (figure 8).

The association between these landforms and colder water is due to their higher elevation and groundwater storage. The majority of the monitoring stations located with these landforms had maximum water temperatures that remained below the water quality standard despite having variable shade levels.

However, there are streams situated within these landforms that have abnormally elevated water temperatures. Some of these stations, located within the upper Yakima drainage, such as the Cooper River, Mineral Creek, and the Waptus River experience water temperatures above expected levels due to heat storage within their drainages in the form of lakes. The same is true

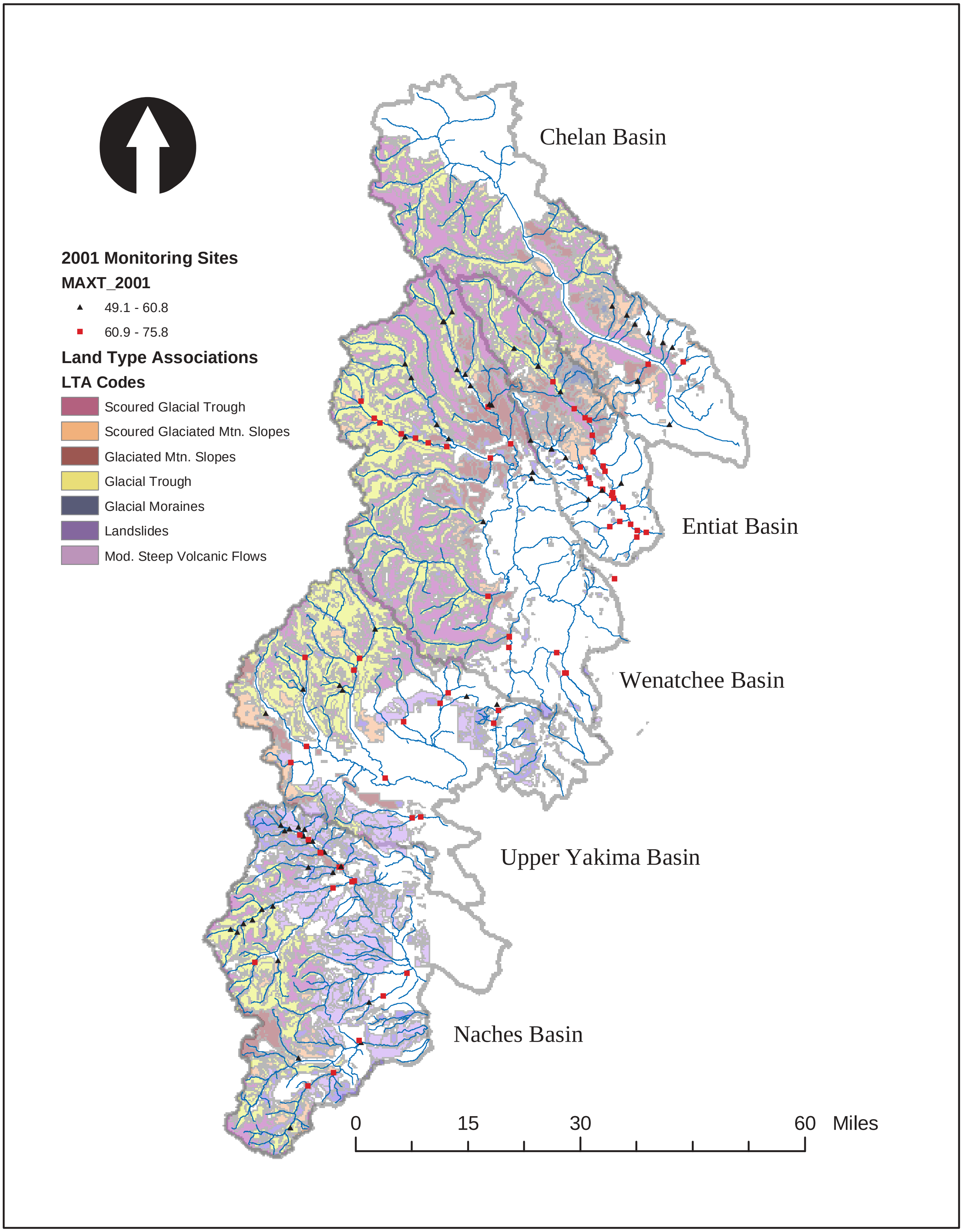

Figure 8. Landforms associated with cooler streams.

for the lower Bumping River (due to Bumping Lake reservoir) in the Naches drainage and Lake Creek in the Wenatchee drainage.

For others, such as the Little Wenatchee River, the Little Naches River, and the lower South Fork Tieton, channel morphological changes (wide, shallow channels) due to high sediment loading combined with low shade levels have resulted in elevated water temperatures. The lower reaches of Sand Creek and Crow Creek - two tributaries to the Little Naches River - also display similarly elevated water temperatures despite proximity within these colder water landforms, again the reason is likely the result of low shade levels. So proximity within these landforms does not preclude streams from experiencing warmer water temperatures. However, elevated water temperatures within these landforms, given the associated conditions of high groundwater inflow, are indicative of low shade characteristics, the result of sediment-related channel widening and (or) loss of a shade producing riparian vegetative buffer.

<u>Effective Shade Levels</u>

Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. It is the principal analysis parameter of this TMDL. The load allocations, or the bottom-line result of the TMDL analysis, are based on establishing effective shade levels necessary to meet the water temperature standard.

Because of its importance, the average percent effective shade was determined for 75 of the 137 monitoring stations. (refer to the Technical Analysis section for information on the methods.) The percent effective shade reported here reflects the average level calculated approximately 2-kilometers above the monitoring station locations. Table 4 presents a statistical overview of the relationship between several ranges of observed maximum water temperature and corresponding effective shade levels. (While it is recognized that there are many factors involved in the heating of surface waters these relationships point to the importance of effective shade levels in determining maximum temperatures.)

Table 4. The relationship between maximum water temperature and associated percent effective shade for 75 streams within the Wenatchee National Forest.

Maximum Temp. Range	N	Median of Range	Effective shade (%) Max	Effective Shade (%) Min	Effective Shade (%) Median
50 – 55	13	54.1	97	34	74
55 – 60	27	58.0	98	25	60
60 – 65	21	62.8	80	22	46
65 +	14	68.0	66	12	36

The coldest streams, those with a maximum temperature range between 50 to 55 ^{o}F had the highest median percent effective shade (74%), while the warmest streams, those above 65^{o}F, had the lowest effective shade levels, with a median level of 36%. The coldest streams are those with groundwater discharge providing a large portion of their in-stream flow and are, therefore, buffered from wide temperature variations. This is evident in the wide variation in percent effective shade present in this group in relation to the maximum temperature. While shade levels were the highest for this temperature range, they probably have less bearing on the maximum water temperature realized. The high effective shade is likely the result that the streams represented within this group tend to be narrower first and second order streams that are more easily shaded. At the upper extreme (65°F+), higher order streams are represented that are wider and have a reduced potential for higher effective shade levels. The range of percent effective shade within this group is lower (54%) and the maximum level calculated (66%) was the lowest among the four groups.

This relationship is plotted in figure 9. (The data presented in figure 9 excludes the warm-water and cold-water stations discussed earlier.) A generalization from this collective data is that a percent effective shade level of approximately 60% is required to maintain water temperatures below the water quality standard. As mentioned earlier, for the coldest streams the temperature standard will likely always be maintained regardless of effective shade levels while for the warmest sites percent effective shade levels greater than 60% would be required.

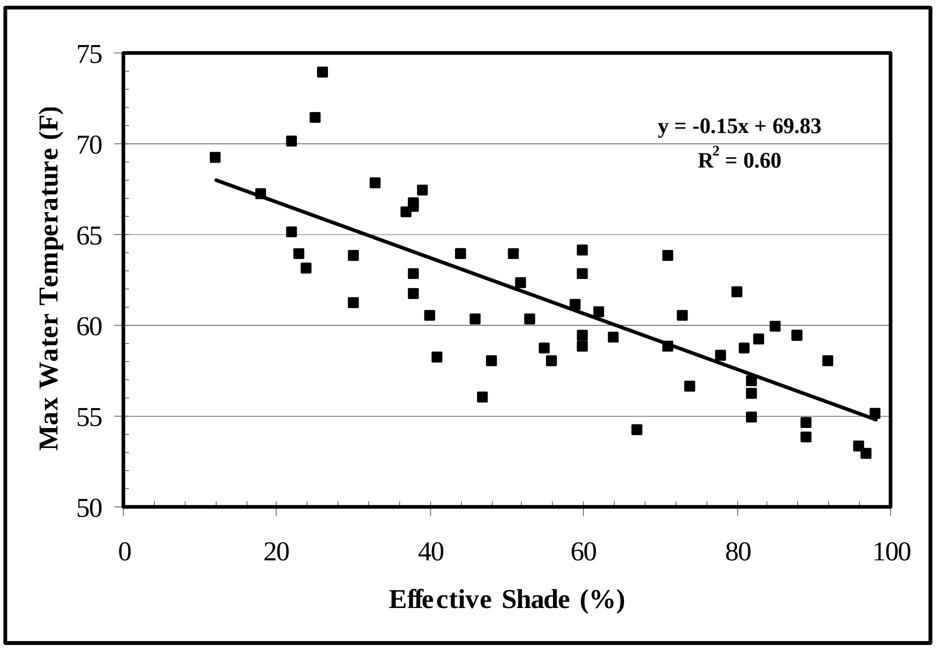

Figure 9. The relationship between percent effective shade and maximum water temperatures observed at monitoring stations.

Another variable affecting maximum water temperatures is elevation. The relationship between elevation and the maximum water temperature observed at the monitoring sites is presented in figure 10 (warm-water and cold-water stations have been excluded). Elevation implicitly incorporates a number of factors among them potential night-time cooling by convection, the type of natural riparian vegetation present, and the relative influence of groundwater cooling. These factors are apparent in this relationship; the highest elevations have the coldest maximum water temperatures and the lowest elevation have among the highest maximum water temperatures. Based on this relationship, the predicted elevation above which the temperature standard is likely to be met is approximately 2600 feet.

Both elevation and percent effective shade were considered as independent variables in a multiple regression equation to predict maximum water temperatures within the Wenatchee Forest. The results of the regression - and additional statistical tests associated with it - are provided in table 5. The dataset was comprised of the monitoring sites where effective shade was calculated with the exclusion of the warm-water and cold-water stations. Because of the significance of these relationships this regression equation provides a generalized approach to establish target shade levels required to meet the water temperature standard. Other analysis methods will be used later in this TMDL to establish load allocations (effective shade levels), however, the results of the regression provide a guide for the shade levels likely required.

Table 6 provides the results of the effective shade levels required to meet the temperature standard for various elevations based on application of the regression equation. The lowest elevations on the Wenatchee National Forest occur within the Entiat River basin at approximately 1500 feet. However, the majority of perennial surface water drainage within the forest is situated between approximately 2000 to 4000 feet. If it is assumed that the majority of the surface water drainage above approximately 3000 feet will likely always meet the temperature standard due to factors mentioned earlier, then the percent effective shade levels required to meet the temperature standard lie between approximately 50 and 80%.

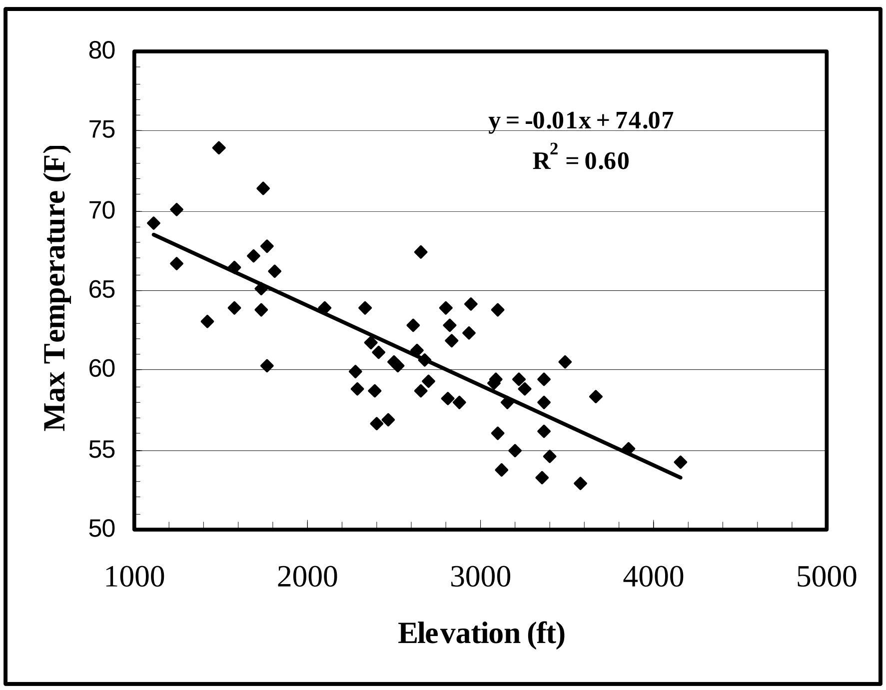

Figure 10. The relationship between elevation and maximum water temperatures observed at monitoring stations.

Table 5. Results of a multiple regression to predict maximum water temperature.

Regression Statistics						
Multiple R	0.83					
R Square	0.68					
Adjusted R Square	0.67					
Standard Error	2.68					
Observations	57					
ANOVA						
	Df	**SS**	**MS**	**F**	**Significance F**	
Regression	2	839.6084	419.8042	58.4275	3.12E-14	
Residual	54	387.9922	7.1850			
Total	56	1227.6006				
	Coefficients	**Standard Error**	**T Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	73.4010	1.3405	54.7553	5.343E-49	70.7134	76.0886
Effective Shade (%)	-0.0888	0.0230	-3.8661	2.992E-04	-0.1349	-0.0428
Elevation (ft)	-0.0028	0.0008	-3.6892	5.241E-04	-0.0043	-0.0013

Table 6. The minimum percent effective shade required to meet the temperature standard (60.8 ^{o}F) based on elevation.

Elevation (ft)	Effective Shade (%)
1000	100+
1500	95
2000	79
2500	63
3000	47
3500	32
4000	16

Seasonal Variation

Clean Water Act Section 303(d)(1) requires that TMDLs "be established at levels necessary to implement the applicable water quality standards with seasonal variations".

Existing conditions for stream temperatures throughout the Wenatchee National Forest reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. The highest water temperatures typically occur from July through August. This time frame was used as the critical period for development of this TMDL.

Seasonal estimates for stream flow, solar flux, and climatic variables were considered in developing critical conditions for TMDL model assumptions. The critical period for evaluation of solar flux and effective shade was assumed to be August 1 because it is the mid-point of the period when water temperatures are typically at their seasonal peak coincident with low flow levels.

Technical Analysis

Landscape Scale Analyses

TMDL development for non-point pollution sources presents some inherent challenges. Diffuse sources are often associated with watershed or landscape scale features and processes occurring over time. Consequently, water quality concerns associated with non-point source (NPS) pollutants require a different approach from traditional point source problems.

Classification systems have been developed to better understand the inherent characteristics and sensitivities of diverse landscapes, and how long-term land management plans interact with them. They are designed to account for the essential influences (e.g. geologic setting, climatic factors) that are largely responsible for much of the natural variation in habitat types at various spatial and temporal scales. The landscape stratification system used, combined with information compiled in development of the channel classification system, provided a technical basis to support assumptions used in the heat budget analysis.

A classification system was developed for the Wenatchee National Forest based on three attributes: geologic setting, drainage area, and channel morphological characteristics.

Geologic Setting

Stratifying the landscape into Subsection Mapping Units (SMU) captures influences of geologic setting and associated physical processes within the Wenatchee National Forest. In 1994, the Wenatchee N.F. completed a subsection level of ecological stratification intended for subregional planning, which is explained in the *"National Hierarchical Framework for Ecological Units"*. Subsection Mapping Units are designed to contain broad areas with similar geomorphic history and expression (landforms), potential natural vegetation patterns, climatic conditions, and soil development. The Wenatchee National Forest includes nine SMUs described in table 7 and figure 11.

Table 7. Description of subsection codes.

Subsection Code	Description
M242 – Ca Wenatchee Highlands	Elevation Range – 2500 – 9500' Precipitation – 50 – 160" Primary Landscape Setting Glacial Cirques Natural Vegetation = Alpine meadows, Mountain Hemlock Trough Walls Natural Vegetation = Mountain Hemlock, Silver Fir series Trough Bottoms Natural Vegetation = Pacific Silver Fir, Western Hemlock series, wet meadows
M242 – Cb	Elevation Range – 1100 – 8000'

Chelan and Sawtooth Highlands	Precipitation – 15 – 55” <u>Primary Landscape Setting</u> Glacial Cirques (above 6500’) Natural Vegetation = Alpine meadows, subalpine larch, whitebark pine, subalpine fir Glacial Trough Walls (1100 – 6500’) Natural Vegetation = Doug. Fir, Grand Fir, subalpine fir series (high elevations). Ponderosa pine series, grassland shrub steppe (lower elevations) Trough Bottoms (lower elevations) Natural Vegetation = Doug. Fir, Ponderosa Pine series associated with shrub-steppe
M242 – Cq Entiat – Chelan Hills	Elevation Range – 1000 – 6700’ Precipitation – 15 – 59” <u>Primary Landscape Setting</u> Glacial Moraines (5000’+) Natural Vegetation = Subalpine fir, Grand Fir series Highly Dissected Hill Slopes (1000 – 5000’) Natural Vegetation = Ponderosa Pine within shrub-steppe at lower elevations, Doug. Fir and grand fir in the upper elevations.
M242 – Ci Cle Elum / Lake Wenatchee Mountain Valleys	Elevation Range – 1900 – 4200’ Precipitation – 30 – 80” <u>Primary Landscape Setting</u> Valley Bottoms (low to mid-elevations) Natural Vegetation = Doug. Fir, Grand Fir, W. Hemlock, sedge/willow meadows Glacial Moraines (mid to high elevations) Natural Vegetation = Doug. Fir, grand fir, W Hemlock
M242 – Cm Wenatchee – Swauk Sandstone Hills	Elevation Range – 1000 – 5000’ Precipitation – 15 – 49” Stream flows are usually intermittent or perennial streams have interrupted flows <u>Primary Landscape Setting</u> Dissected Sandstone Hills Natural Vegetation = Ponderosa Pine associated with shrub-steepe (lower elevations), Doug. Fir series (mid to upper elevations).

M242 – Cn Upper Yakima – Swauk Sandstone Hills	Elevation Range – 2500 – 7000' Precipitation – 30 – 50" <u>Primary Landscape Setting</u> Dissected Sandstone Hills Natural Vegetation = W. Hemlock, Grand Fir (western portion), Grand Fir, subalpine fir (eastern portion).
M242 – Co Upper Yakima Basin	Elevation Range – 2500 – 9500' Precipitation – 50 – 160" Near surface ground water, seeps, and springs on lower slopes helps to maintain base flows and low stream temperatures. <u>Primary Landscape Setting</u> Glacial Mountains (upper elevations) Natural Vegetation = W. Hemlock, Pac. Silver Fir, Mountain Hemlock. Dissected Ridges (low to mid elevations) Natural Vegetation = W. Hemlock, Pac. Silver Fir and Grand Fir (eastern portion)
M242 – Cp Naches Mountains	Elevation Range – 2500 – 7700' Precipitation – 40 – 99" Near surface ground water, seeps, and springs on lower slopes helps to maintain base flows and low stream temperatures. <u>Primary Landscape Setting</u> Glacial Mountains (upper elevations) Natural Vegetation = Pac. Silver Fir and Mtn. Hemlock Volcanic & Pyroclastic Flows Natural Vegetation = Subalpine Fir (upper elevations), Grand Fir (mid elevations), Doug. Fir (lower elevations). Dissected Mountain Slopes Natural Vegetation = Silver Fir (W. portion), Grand Fir (E. Portion, low elevation), Subalpine Fir (E. portion, upper elevation)
M242 – Cc Cascade Mountains, Non-glaciated	Elevation Range – 2000 – 6000' Precipitation – 10 – 50" <u>Primary Landscape Setting</u> Plateaus and Mountain Slopes Natural Vegetation = Ponderosa Pine associated with shrub-steppe

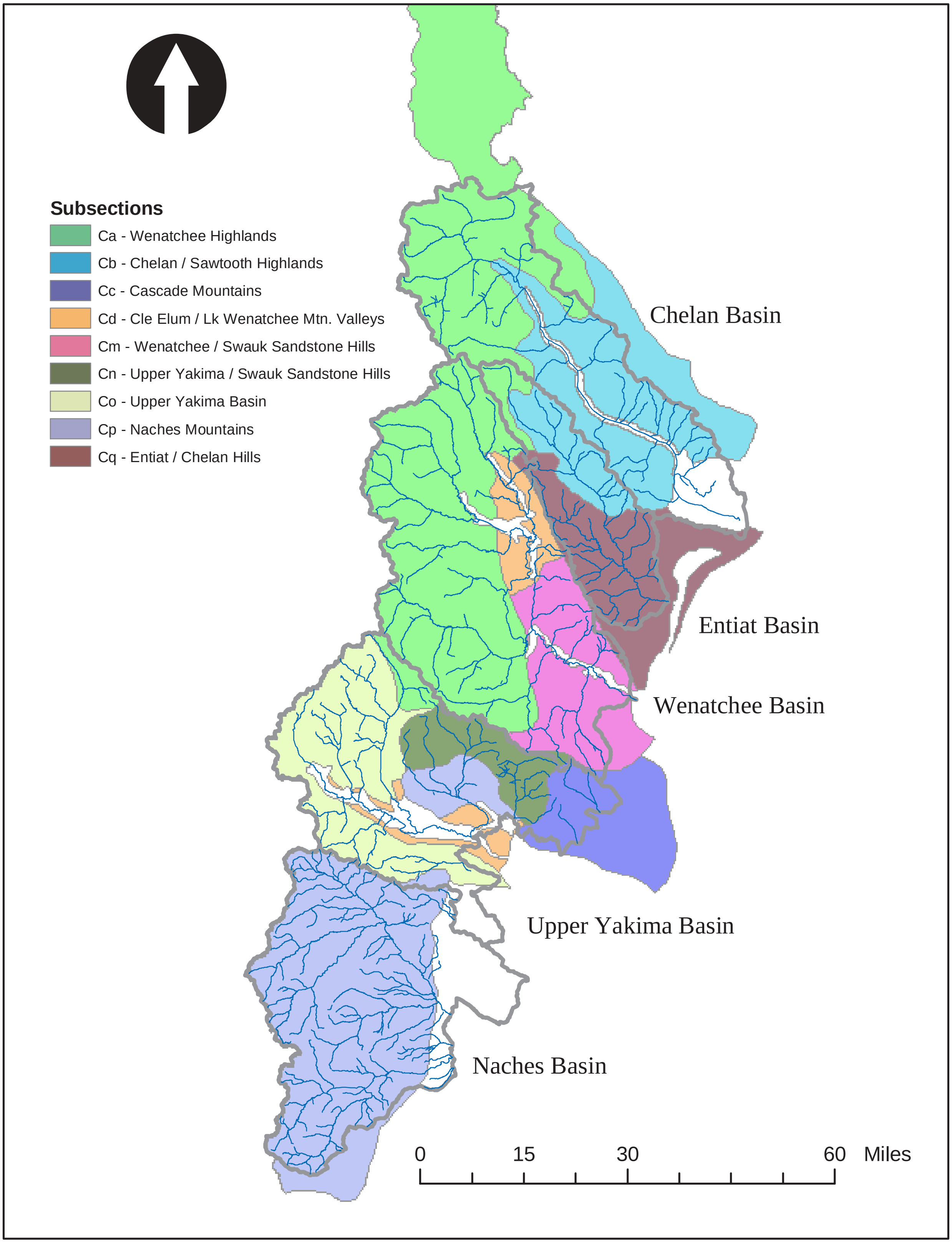

Figure 11. Subsections within the Wenatchee National Forest.

Drainage Area

Both watershed size and stream order are important in assessing water temperature. Hydraulic geometry relationships should be stratified not only by stream type, but also by watershed size (Rosgen, 1996). For example, the relative roughness ratio is much less, and the average velocity greater, for a relatively large C stream type (e.g. bankfull width of 200–300 feet), than that of a small C stream type (e.g. bankfull width of 10-20 feet).

Stream order has long been used by hydrologists to develop quantitative relationships and is often used to describe stream size. A 1:24000 scale digitized stream layer covering the Wenatchee National Forest was used to develop a relationship between relative stream size and drainage area at each water temperature monitoring location. A geometric progression in drainage area size that captured the greatest number of orders was determined for the forest (table 8). The bankfull width presented in table 8 was determined based on an evaluation that related drainage area to bankfull width observed at USGS gauging stations in proximity to the Wenatchee National Forest (figure 12).

Table 8. Relationship between stream size and drainage area (acres) observed at monitoring locations.

Relative Size	Drainage Area (acres)	Bankfull Width (ft)
1	X<=2000	16
2	2000<x<=5000	20
3	5000<x<=12500	31
4	12500<x<=31250	47
5	31250<x<=78125	70
6	78125<x<=195313	106
7	195313<x<=488281	160

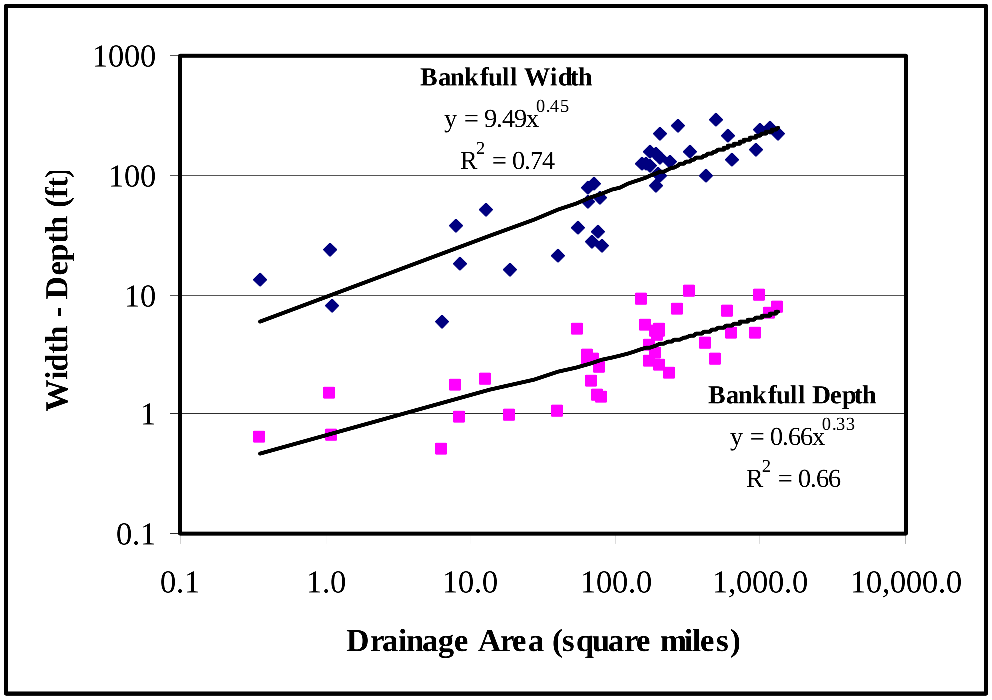

Figure 12. The relationship between drainage area and bankfull width and depth observed at historic and current USGS gauging stations within, and proximal to, the Wenatchee National Forest .

Channel Classification

Conditions in a stream are a function of channel morphology (e.g. source, transport, or response reaches). Methods exist to assess the condition of a stream, as well as departure from its potential (Rosgen, 1996). These methods, built around channel classification, are useful to develop specific TMDL surrogate measures for streams in the Wenatchee National Forest. Consequently, a second lower level of stratification consists of classifying stream segments of the channel network within each of the subsections.

Rosgen has developed a broad-level delineation system, which allows for a rapid initial morphological classification of stream types that are typically encountered within watersheds. The system provides a framework for organizing and assessing information within each Subsection Map Unit. Table 9 describes the major stream types used in development of this TMDL.

Table 9. Stream-type descriptions (Rosgen, 1996).

Stream Type	General Description	Bankfull W:D Ratio	Slope (%)	Landform / Soils / Features
A	Steep, entrenched, cascading step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel	<12	4 – 10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step/pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks.	>12	2-4	Moderate relief, colluvial deposition, and/or structural. Moderate entrenchment and w/d ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools.
C	Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well defined floodplains.	>12	<2	Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/pool bed morophology.
E	Low gradient, meandering riffle/pool stream with w/d ratio and little deposition. Very efficient and stable. High meander width ratio.	<12	<2	Broad valley/meadows. Alluvial materials with floodplains. Highly sinuous with stable, well vegetated banks. Riffle/pool morphology with very low w/d ratios.

Mechanistic Water Temperature Models

Mechanistic models have been developed, based on a heat budget approach, which estimate water temperature under different heat balance and flow conditions. Brown (1969) was the first to apply a heat budget to estimate water temperatures on small streams affected by timber harvest. Using mathematical relationships to describe heat transfer processes, the rate of change in water temperature on a summer day can be estimated. Relationships include both the total energy transfer rate to the stream (i.e. the sum of individual processes) and the response of water temperature to heat energy absorbed. Heat transfer processes considered in the analysis include solar radiation, longwave radiation, convection, evaporation, and bed conduction (Wunderlich 1972, Jobson and Keefer 1979, Beschta and Weatherred 1984, Sinokrot and Stefan 1993).

Solar radiation is the predominant energy transfer process that contributes to water temperature increases. A general relationship between solar radiation loads and stream temperature can be developed by quantifying heat transfer processes, providing a starting point to defining a loading capacity (i.e. the greatest amount of loading that a water-body can receive without violating water quality standards).

QUAL2K and Response Temperature Model

QUAL2K (Chapra, 2001) and the Response Temperature models were used to calculate the components of the heat budget and to simulate water temperatures. QUAL2K, a Visual Basic application in a Microsoft Excel® environment, uses the kinetic formulations for the surface water heat budget described above and presented in Chapra (1997). In summary, QUAL2K is a steady-state, one-dimensional model that simulates diurnally varying water temperature using a finite-difference numerical method. Therefore, a single flow condition is selected to represent a given condition, such as a seven-day average flow. For temperature simulation, solar radiation, air temperature, relative humidity, headwater temperature, and point source/tributary water temperatures are specified as diurnally varying functions with a minimum and maximum value and time of the maximum value.

The concept of response temperature was originally proposed by J.E. Edinger Associates. Response temperature is defined as the temperature that a column of fully mixed water would have if heat fluxes across the surface were the only heat transfer processes. In other words, the water temperature is assumed to be responding only to those heat fluxes.

The rate of surface heat exchange can be calculated from meteorological data (e.g. air and dew point temperature, wind speed, cloud cover, solar radiation). Edinger et al (1974) provides an excellent and comprehensive review of the methods that can be used to estimate heat fluxes. Because meteorological data are available for long periods, this simple model provides the basis to estimate long-term, frequency of occurrence statistics for natural water temperatures.

The Department of Ecology has extended this concept to include the response to heat flux between the water and the stream bed, groundwater inflow, and hyporheic exchange. The rate of change of response temperature can be written in terms of the net rate of surface heat exchange as:

dT/dt = Jnet / (D*rhow*Cpw)

dT/dt	The rate of change of water temperature with time (^{o}C per second)
D	The mean depth of the water column (centimeters)
Jnet	The net rate of surface heat exchange (solar shortwave, longwave atmospheric, longwave back, convection, evaporation, streambed conduction, hyporheic exchange, groundwater inflow) (calories/square-centimeter/second),
Rhow	The density of water (1 gram/cubic-centimeter),
Cpw	The specific heat of water at constant pressure (calorie/gram/ ^{o}C).

A similar expression can also be written for the change in temperature of the surface layer of the bottom sediment underlying the stream bed in response to the heat flux from hyporheic exchange and conduction between the water and sediment.

Effective Shade Calculations

Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. Effective shade is a function of several landscape and stream geometric relationships including:

- latitude and longitude
- time of year
- stream aspect and width
- vegetation buffer height, width, overhang, and canopy density
- topographic shade angles

As part of this analysis, the average effective shade was calculated above 75 of the 137 temperature monitoring stations. The analysis methods used to determine effective shade are outlined below.

An Arc-View 3.2 project was constructed from the following files:

- 2001 USFS monitoring stations and surface waters throughout the forest (digitized at a 1:24000 scale).
- Grid files obtained from the USFS (Wenatchee) included 25-meter resolution of vegetative diameter breast height (DBH) and canopy density. The grid breakdown of the canopy density was as follows:

Open Canopy	0 – 10%
Low Density Canopy	10 – 40%
Medium Density Canopy	40 – 70%
High Density Canopy	70%+

The grid breakdown of the diameter breast height (DBH) was as follows:

Shrub / Seedling	0.1 – 3 inches
Sapling / Pole	>3 – 8 inches
Small Tree	>8 – 16 inches
Medium Tree	>16 – 25 inches
Large Tree	> 25 inches

- Digital elevation model grid with a 10-meter resolution
- USFS (Wenatchee) polygon coverage of Land Type Associations

Arc-view based extensions used in this analysis included: Spatial Analyst, CRWR-Raster V. 1.0 (http://www.ce.utexas.edu/prof/olivera/header.htm), Mila Grid Utilities 1.3 (http://www.mila.ucl.ac.be/logistique/sig/sig-tools/), X-Tools (http://www.odf.state.or.us/divisions/management/State_forests/XTools.asp), T-Tools (http://www.deq.state.or.us/wq/TMDLs/WQAnalTools.htm).

T-Tools, an extension of Arc-View 3.2, was used to sample two-kilometer sections above the 63 monitoring stations. Based on a user defined stream length and sampling interval, T-Tools samples for the following parameters: aspect, elevation, gradient, topographic shade, channel width and riparian canopy density and height. Each parameter was determined at an internal length of 30.5 meters for two-kilometers above each monitoring location. At each 30.5 meter interval, canopy density and vegetative height was sampled at 9, 4.6 meter intervals orthogonal to the centerline of the stream for both the left and right bank. This data was then imported into an Excel-based effective shade calculator maintained by the Washington State Department of Ecology (http://www.ecy.wa.gov/programs/eap/models/index.html).

The determination of the effective shade associated by riparian vegetation is based on the height (shadow length) of the vegetation and its canopy density. While canopy density was available as a grid file, the stand height was not. So, the relationship between diameter breast height and stand height was determined. A Wenatchee Forest dataset, comprised of 3829 measurements of diameter breast height and stand height for a variety of species, was used to determine this association. Initially, the data were analyzed by species. For the majority of the dominant species found in the forest, the relationship between dbh and height was similar and so the data were combined and a single relationship determined. A statistical overview of the results of this analysis is presented in table 10. (The size ranges in dbh reflect grid values.) With the relationship established, the diameter breast height grid was reclassified based on the mean tree height by dbh range. The CRWR-raster extension was then used to merge the two grids into a single coverage for sampling with the t-tools extension.

Table 10. Statistical overview of the relationship between tree height (feet) for specific ranges in diameter breast height (DBH) (inches).

	Diameter Breast Height (inches)			
	3 – 8	**8 – 16**	**16 – 25**	**25+**
Mean	50 feet	81 feet	104 feet	129 feet
Standard Error	3.00	0.41	0.41	1.00
Median	52	82	104	128
Mode	49	87	95	130
Standard Deviation	11.23	15.72	16.90	24.21
Sample Variance	126.22	247.03	285.66	586.31
Kurtosis	-0.371	-0.094	-0.026	0.433
Skewness	-0.704	-0.149	-0.007	0.407
Range	35	97	113	158
Minimum	30	30	44	67
Maximum	65	127	157	225
Sum	704	121434	180080	75524
Count	14	1496	1734	585
Confidence Level - 95.0%	6.49	0.80	0.80	1.97

Potential Natural Vegetation

Effective shade produced by optimal growth conditions was determined for the forest. This calculation served as the load allocation. To determine optimal growth, the dbh/stand height and canopy density grids were sampled by subsection. The most common stand height and canopy density represented within each subsection were assumed to represent background or optimal growth. The results of this analysis are presented in table 11. This data served as input to the effective shade calculator discussed earlier.

For additional background information, an overview of the percent effective shade for varying tree heights, canopy densities and stream widths is presented in table 12. (This table represents the shade levels generated using grid values.) The bankfull width covers the range expected for streams within the forest.

Table 11. Assumed tree height and canopy density, by subsection, used to calculate site potential effective shade.

Subsection	Stand Height (m)	Canopy Density (%)
Ca Wenatchee Highlands	32	70
Cb Chelan & Sawtooth Highlands	24	70
Cc Cascade Mountain	15*	27*
Cd Cle Elum / Lk Wenatchee Mtn. Valleys	32	70
Cm Wenatchee / Swauk Sandstone Hills	18*	35*
Cn Upper Yakima / Swauk Sandstone Hills	28	70
Co Upper Yakima Basin	32	70
Cp Naches Mtn.	32	70
Cq Entiat / Chelan Hills	13*	22*

*** Weighted Average**

Table 12. Percent effective shade generated by varying stand height and canopy density, assuming a 45-degree aspect and no topographic influence. (Stand height and canopy density levels are based on respective grid values.)

Stand Height (m)	**Canopy Density (%)**	**Bankfull Width (m)**								
		1	**3**	**8**	**11**	**16**	**23**	**30**	**45**	**60**
40	**70**	99	97	90	76	58	51	44	33	26
	55	98	95	74	59	43	38	33	25	19
	25	83	58	34	26	19	16	14	11	9
	5	68	27	10	7	5	4	4	3	3
32	**70**	98	97	82	66	55	47	40	29	22
	55	98	94	65	51	42	36	31	22	17
	25	83	58	31	23	19	16	14	10	8
	5	69	27	9	7	5	4	4	3	3
24	**70**	98	96	69	59	51	42	34	23	17
	55	97	94	55	46	40	33	27	18	13
	25	83	59	26	21	18	15	12	9	7
	5	68	27	8	6	5	4	4	3	3
15	**70**	98	91	57	50	41	31	24	15	10
	55	97	80	45	40	32	25	19	12	9
	25	83	48	22	20	16	12	10	7	5
	5	68	25	8	6	5	4	4	3	3
3	**70**	84	52	23	16	10	6	4	3	2
	55	80	44	19	13	8	5	4	2	2
	25	71	31	11	8	5	4	3	2	1
	5	65	22	6	5	4	3	2	1	1

Loading Capacity

Regulatory Framework

Under the current regulatory framework for development of TMDLs, identification of the loading capacity is an important first step. The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring a water into compliance with standards. By definition, TMDLs are the sum of the allocations *[40 CFR §130.2(i)]*.

Allocations are defined as the portion of a receiving water's loading capacity that is allocated to point or nonpoint sources and natural background. EPA's current regulation defines loading capacity as *"the greatest amount of loading that a water can receive without violating water quality standards"*.

The foundation of a TMDL analysis is the water quality standard. It provides the basis from which the fundamental TMDL calculations are made - among them the load capacity and load allocation. (For surface waters within the Wenatchee National Forest, the temperature standard is 60.8^{o}F (16^{o}C).) Heat is the pollutant in this TMDL, and the load capacity is based on determining what level reduction in heat is necessary to achieve the standard for temperature impaired surface waters. As discussed earlier, rather than setting the load capacity based on heat, the surrogate measure percent effective shade has been used.

Within this analysis, the TMDL allocation is the percent effective shade necessary to reduce water temperatures to the water quality standard while the load allocation is the percent effective shade provided by site potential vegetation. Site potential vegetation has maximum tree height and canopy density (principal shade producing attributes) expected for a particular area. Therefore, the shade produced by site potential vegetation represents the maximum that can be produced naturally.

<u>Natural Conditions</u>

A complication in using mechanistic models to develop load allocations (in terms of effective shade) is that the result may not be achievable. This occurs when the mature riparian area is not tall enough or have sufficient density to shade the entire active channel. For instance, on June 21 the shadow length of a 170 foot tall Douglas fir at 1pm (daylight time) is about 75 feet. This means that an active channel wider than 75 feet will not be completely shaded on that date.

For such cases, and for cases where the numeric criteria is naturally exceeded, the natural conditions clause of Washington's water quality standards is applied [WAC 173-201A-070(2)]. This means that where mature riparian vegetation will not fully shade the active channel, the temperature that results from shade achievable by mature riparian vegetation becomes the standard.

Because of the structure of this analysis, the TMDL and load allocations will be presented in the following section.

Load Allocations

Under the current regulatory framework for development of TMDLs, flexibility is allowed for specifying allocations. TMDLs can be expressed in terms of either mass per time, toxicity, or other appropriate measures. This TMDL assessment uses percent effective shade as a surrogate measure of heat flux to fulfill the requirements of Section 303 part (d) of the Clean Water Act. Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. In contrast, allocations could have taken the form of energy per unit area (heat load), however, that measure is less relevant in guiding management activities needed to solve identified water quality problems. Percent effective shade can be linked to specific source areas, and thus to actions (specifically riparian management) needed to solve problems that cause water temperature increases. For this reason, shade is used as a surrogate to the thermal load as allowed under EPA regulations (defined as “other appropriate measure” in 40 CFR §130.2(i)).
This TMDL develops load allocations based on a channel classification system developed for surface waters within the Wenatchee National Forest. Table 13 outlines the load allocations, load capacity and margin of safety as percent effective shade for each stream class. (Refer to the technical analysis section for a complete explanation of the classification system and its development.)

Table 13. The TMDL allocation, load allocation, and margin of safety by channel class.

Classification	Flow (cfs)	W:D (wetted)	TMDL Allocation Effective Shade (%)	Load Allocation Effective Shade (%)	Margin of Safety Effective Shade (%)
M242Ca Wenatchee Highlands					
Ca-3C	4.0	30.0	75*	74	-
Ca-4C	8.0	35.0	70*	57	-
Ca-5C	16.0	40.0	65*	49	-
Ca-6C	32.0	45.0	60*	38	-
M242Cb Chelan & Sawtooth Highlands					
Cb-1A	1.0	10.0	80	91	9
Cb-2A	2.0	10.0	80	82	2
Cb-3C	4.0	30.0	75*	62	-
Cb-4C	8.0	35.0	70*	54	-
Cb-5C	16.0	40.0	65*	44	-
Cb-6C	32.0	45.0	60*	32	-
M242Cd Cle Elum / Lake Wenatchee Mountain Valleys					
Cd-1A	1.0	10.0	80	95	15
Cd-2B	2.0	15.0	80	92	12
Cd-5C	16.0	40.0	65*	49	-
Cd-6C	32.0	45.0	60*	38	-
M242Cm Wenatchee / Swauk Sandstone Hills					
Cm-3C	4.0	30.0	75*	30	-
Cm-4C	8.0	35.0	70*	25	-
Cm-5C	16.0	40.0	65*	19	-
M242Cn Upper Yakima / Swauk Sandstone Hills					
Cn-1A	1.0	10.0	80	93	13
Cn-2B	2.0	15.0	80	89	9
Cn-4C	8.0	30.0	70*	56	-
M242Co Upper Yakima Basin					

Co-2B	2.0	15.0	80	92	12
Co-3C	4.0	30.0	75*	74	-
Co-4C	8.0	35.0	70*	57	-
Co-5C	16.0	40.0	65*	49	-
M242Cp Naches Mountains					
Cp-1A	1.0	10.0	80	95	15
Cp-1B	1.0	15.0	80	95	15
Cp-2B	2.0	15.0	80	92	12
Cp-2C	2.0	25.0	80	92	12
Cp-3B	4.0	20.0	70	74	4
Cp-3C	4.0	30.0	75*	74	-
Cp-4C	8.0	35.0	70*	57	-
Cp-5C	16.0	40.0	65*	49	-
Cp-6C	32.0	45.0	60*	38	-
M242Cq Entiat / Chelan Hills					
Cq-2B	2.0	15.0	80*	22	-
Cq-3C	4.0	30.0	75*	18	-

Table 13 continued

Classification	Flow (cfs)	W:D (wetted)	TMDL Allocation Effective Shade (%)	Load Allocation Effective Shade (%)	Margin of Safety Effective Shade (%)
Cq-4C	8.0	35.0	70*	14	-
Cq-5C	16.0	40.0	65*	11	-
Cq-6C	32.0	45.0	60*	7	-
Cq-7C	64.0			5	-
M242Cc Cascade Mountain: Non-Glaciated					
Cc-1A	1.0	10.0	80*	32	-
Cc-2B	2.0	15.0	80*	27	-
Cc-4C	8.0	35.0	70*	18	-
Cc-5C	16.0	40.0	65*	14	-
Cc-6C	32.0	45.0	60*	10	-

***TMDL allocation defaults to the load allocation (site potential vegetation).**

Based on the classification scheme presented in table 13**,** along with associated allocations, the percent effective shade applicable for streams throughout the forest can be extrapolated.

The Cooper River provides an example of how table 13 is applied. In order to use table 13, the classification appropriate to a particular stream section of interest must first be determined. In review, the classification system is based on three attributes: subsection, stream size (based on drainage area), and Rosgen channel class. So, for instance, the Cooper River which has a classification of Co-4C, is located within the Upper Yakima Basin (subsection Co), has a stream size of 4, with a Rosgen channel class of C.

The first step to determining the TMDL allocation appropriate to a particular stream section is to identify what subsection it lies within. Figure 11 provides a map of the subsections within the Wenatchee Forest with the major forest basins outlined. Referring to figure 11, the Cooper River, which discharges to the Cle Elum River above Kachess Lake, is located in the Upper Yakima Basin subsection (Co).

The next step is to determine the drainage area (in acres) located above the stream section. Table 8 provides a breakdown of the relationship between drainage area and stream size. Based on its drainage area, in reference to the 2001 monitoring location (approximately 24000 acres), and referring to table 8, it is a stream size 4.

Table 9 provides general descriptions and channel characteristics (bankfull width to depth ratios, channel slope) by channel class (refer to Rosgen, 1996 for additional channel class attributes). The lower Cooper River with bankfull width to depth ratio greater than 12 and a slope less than 2, place it as a C-type channel.

Based on these attributes, the Cooper River at the monitoring location has a channel classification of Co-4C. Referring to table 13, a Co-4C has a TMDL allocation of 70% effective shade. However, the load allocation, which is based on site potential vegetation, is 57% effective shade, a lower level than the TMDL allocation. The TMDL allocation is the percent effective shade necessary to reduce water temperatures to the water quality standard. In comparison, the load allocation is the percent effective shade provided by site potential vegetation. Site potential vegetation has maximum tree height and canopy density (principal shade producing attributes) expected for a particular area. For this analysis, site potential vegetation was determined by subsection. So, in the case where the load allocation (site potential vegetation) is less than the TMDL allocation, the load allocation value applies. The reason for this is that the allocation for shade cannot go beyond what can be produced naturally. For this reason, the percent effective shade allocation of 57% is determined.

Direct application of table 13 to the listed and impaired streams is provided in tables 14 and 15.

Table 14. Allocations (as percent effective shade) for water bodies within the Wenatchee National Forest included on the 1996 and 1998 303(d) lists for water temperature.

Water Body	**1996 WBID**	**Township, Range, Section**	**Stream Classification**	**TMDL Allocation** **Effective Shade (%)**	**Load Allocation** **Effective Shade (%)**
Cooper R.	WA-39-1055	22N,14E,16	Co-4C	70*	57
Gale Ck.	WA-39-1300	22N,13E,32	Co-2B	80	92
Gold Ck.	WA-39-1390	22N,11E,01	Cb-3C	75*	62
Iron Ck.	WA-39-1440	21N,17E,03	Cn-2B	80	89
SF Manastash Ck.	WA-39-3025	18N,15E,36	Cc-4C	70*	18
SF Taneum Ck.	WA-39-1570	19N,15E,27	Co-4C	70*	57
Waptus R.	WA-39-1057	22N,14E,04	Co-5C	65*	49
Blue Ck.	WA-39-1435	21N,17E,02	Cn-1A	80	93
American R.	WA-38-1060	17N,13E,12	Cp-5C	65*	49
Bear Ck.	WA-38-1088	19N,13E,32	Cp-2B	80	92
NF Nile Ck. (Benton)	WA-38-2110	16N,15E,03	Cp-1A	80	95
Bumping R.	WA-38-1070	17N,13E,12	Cp-5C	65*	49
Crow Ck.	WA-38-1081	18N,14E,30	Cp-4C	70*	57
Gold Ck.	WA-38-1041	17N,14E,36	Cb-2A	80	82
Mathew Ck.	WA-38-1086	18N,13E,10	Cp-2B	80	92
SF Tieton R.	WA-38-3000	13N,13E,13	Cp-5C	65*	49
Rattlesnake Ck.	WA-38-1035	15N,14E,10	Cp-5C	65*	49
Little Wenatchee R.	WA-45-4000	27N,16E,15	Ca-5C	65*	49

***TMDL allocation defaults to the load allocation (site potential vegetation).**

Table 15. Allocations (as percent effective shade) for water bodies where water temperatures were observed at levels exceeding the 60.8°F water quality standard in 2001.

Water Body	Stream Name	Township, Range, Section	Stream Classification	TMDL Allocation Effective Shade (%)	Load Allocation Effective Shade (%)
HAUS_01	Hause Ck.	14N, 14E, 21	Cp-2B	80	92
SFTI_01	South Fork Tieton	13N, 13E, 13	Cp-5C	65*	49
LTRA_02	Little Rattlesnake Ck.	15N, 14E, 25	Cp-3C	75*	74
LTNA_01	Little Naches R.	17N, 14E, 4	Cp-6C	60*	38
LTNA_02	Little Naches R.	18N, 14E, 30	Cp-5C	65*	49
LTNA_04	Little Naches R.	18N, 13E, 14	Cp-5C	65*	49
LTNA_05	Little Naches R.	18N, 13E, 9	Cp-4C	70*	57
LTNA_06	Little Naches R.	18N, 13E, 5	Cp-4C	70*	57
SANDN_01	Sand Ck.	18N, 13E, 14	Cp-2B	80	92
BUMP_01	Bumping R.	17N, 14E, 4	Cp-6C	60*	38
BUMP_03	Bumping R.	17N, 13E, 12	Cp-5C	65*	49
BUMP_06	Bumping R.	16N, 11E, 36	Cp-4C	70*	57
QUAR_01	Quartz Ck.	18N, 14E, 30	Cp-3C	75*	74
GREY_01	Grey Ck.	13N, 13E, 29	Cp-1A	80	95
ENTI_12	Entiat R.	28N, 19E, 33	Cb-6C	60*	32
ENTI_13	Entiat R.	28N, 19E, 29	Cb-6C	60*	32
ENTI_14	Entiat R.	28N, 18E, 2	Cb-6C	60*	32
NFEN_01	North Fork Entiat	29N, 18E, 27	Cb-4C	70*	54
SWAKANE	Swakane Ck.	24N, 20E, 16	Cq-3C	75*	18
ROAR_01	Roaring Ck.	25N, 20E, 8	Cq-4C	70*	14
ROAR_02	Roaring Ck.	25N, 20E, 7	Cq-4C	70*	14
POTA_01	Potato Ck.	27N, 19E, 36	Cq-3C	75*	18
PRES_01	Preston Ck.	28N, 19E, 34	Cb-2A	80	82
MITC_01	Mitchel Ck.	29N, 21E, 24	Cb-2A	80	82
MADR_01	Mad R.	26N, 19E, 13	Cq-5C	65*	11
MADR_02	Mad R.	26N, 19E, 15	Cq-5C	65*	11
MADR_03	Mad R.	26N, 19E, 10	Cq-5C	65*	11
MADR_04	Mad R.	27N, 19E, 33	Cq-4C	70*	14
GRAD_02	Grade Ck.	30N, 21E, 31	Cb-3C	75*	62
LTWE_02	Little Wenatchee R.	27N, 16E, 18	Ca-5C	65*	49
LTWE_03	Little Wenatchee R.	27N, 15E, 11	Ca-5C	65*	49
LTWE_05	Little Wenatchee R.	27N, 15E, 10	Ca-5C	65*	49
LTWE_07	Little Wenatchee R.	28N, 14E, 36	Ca-4C	70*	57
LWTE_09	Little Wenatchee R.	28N, 13E, 14	Ca-3C	75*	74
LAKEW_01	Lake Ck.	28N, 15E, 31	Ca-3C	75*	74
CHWA_01	Chiwawa R.	27N, 18E, 30	Cd-6C	60*	38
CHWA_02	Chiwawa R.	27N, 17E, 13	Cd-6C	60*	38
ROCK_01	Rock Ck.	29N, 17E, 31	Cd-4C	70*	57
SANDW_01	Sand Ck.	22N, 18E, 1	Cm-3C	75*	30
EFMI_01	East Fork Mission	22N, 19E, 18	Cm-4C	70*	25
DEVI_01	Devils Gulch	22N, 19E, 18	Cm-3C	75*	30
IRON_01	Iron Ck.	21N, 17E, 10	Cn-2B	80	89
MINE_01	Mineral Ck.	22N, 13E, 5	Co-2B	80	92
BLUE_01	Blue Ck.	21N, 17E, 22	Cn-2B	80	92
TANE_01	Taneum Ck.	19N, 15E, 25	Co-5C	70*	49
NFTA_01	North Fork Taneum Ck.	19N, 15E, 26	Co-4C	70*	57

***TMDL allocation defaults to the load allocation (site potential vegetation).**

Margin of Safety

The Clean Water Act requires that each TMDL have some margin of safety (MOS) to account for analysis uncertainty occurring, for instance, from a lack of available data, error involved in pollutant loading calculations, or in the effect best management practice implementation will have on loading reductions and receiving water quality. A margin of safety can be expressed as an unallocated assimilative capacity or through the use of conservative analytical assumptions used in establishing the TMDL (e.g., derivation of numeric targets, modeling assumptions or effectiveness of proposed management actions).

Much of the data used in this analysis is based on the monitoring data collected by the USFS during the summer of 2001. Physical conditions represented by both air temperature and stream flow indicate that 2001 was unusual: air temperatures were at historic highs and stream flows at historic lows. These conditions, along with other factors, provided for warmer water temperatures particularly for those water bodies with low effective shade levels. Because of these critical conditions, the analysis results based on the 2001 data provides a high margin of safety.

This TMDL achieved additional margin of safety based on methods used to establish the load allocations. The allocations were set based on the percent effective shade provided by the potential natural vegetation. Optimal vegetation height and canopy density associated with each landform was used in the determination of load allocations. The difference between the TMDL target (allocation) (the effective shade level necessary to meet the temperature standard) and the load capacity (the effective shade level provided by optimal vegetative conditions) was used as the margin of safety (refer to table 13).

A discussion of air temperatures and flow levels observed within, and proximal to, the Wenatchee National Forest during the summer of 2001 is provided below.

<u>Air Temperature – Historic to 2001</u>

Based on air temperature monitoring data collected at stations located within the Wenatchee National Forest, the average maximum and minimum August air temperatures in 2001 were 76.2 ^{o}F and 47.9 ^{o}F, respectively. August 12 was among the warmest days of the summer for most of the sites with average maximum and minimum air temperatures of 90.0^{o}F and 51.5^{o}F, respectively. On August 12, peak air temperature occurred at approximately 3:00 PM and the minimum occurred at approximately 6:30 AM (table 16).

Table 16. Average maximum air temperatures (^oF) observed at several of the Wenatchee monitoring stations during August, 2001 along with the maximum and minimum observed on August 12, 2001.

Monitoring Station	Elevation (feet)	8 / 2001 Max	8 / 2001 Min	8-12-01 Max	Time Max	8-12-01 Min	Time Min
Bearn_01	3133	72.7	46.3	86.1	15:00	49.1	6:00
LTNA_01	2547	77.1	47.5	92.3	14:00	51.8	6:00
LTNA_02	2716	78.2	45.7	92.4	14:00	49.5	6:00
LTNA_03	-	78.1	49.4	89.7	14:00	53.0	7:00
LTNA_04	2930	79.2	46.7	94.6	14:00	49.9	7:00
LTNA_06	3135	71.8	45.3	86.2	15:00	48.2	6:00
MFLN	3363	75.4	44.9	90.5	13:00	47.2	6:00
NFLN	3253	76.8	43.9	93.9	13:00	45.8	6:00
Bump_01	2561	81.6	50.1	94.9	15:00	54.2	6:00
Bump_06	3474	76.6	45.9	94.0	15:00	50.2	7:00
Amer_01	-	77.5	46.9	90.5	14:00	51.8	5:00
Amer_02	-	72.5	45.6	84.8	15:00	51.5	6:30
Amer_04	3630	71.4	44.4	86.9	16:00	48.5	7:00
Amer_05	3655	74.1	43.3	90.1	16:00	47.1	7:00
White_01	1869	73.8	54.1	85.2	18:00	56.7	7:00
LTWE_01	1877	78.4	54.5	87.2	17:30	57.2	6:00
Chwa_01	1768	77.6	51.3	90.3	16:30	55.5	7:00
Chwa_05	2781	75.5	46.7	88.2	15:30	48.6	6:00
Nason_01	1866	79.1	53.8	92.4	15:30	57.1	6:30
Yaki_01	2200	75.2	49.6	90.6	15:00	51.5	6:30
Teanaway	-	76.9	46.8	89.5	14:00	51.5	6:00
Tane_01	2720	71.6	52.6	84.5	14:30	56.6	6:00
Swak_01	-	81.4	46.3	94.2	14:30	51.6	6:00

A comparison was made between air temperatures observed during the study period (summer, 2001) with those observed historically. Several weather stations were chosen for this analysis based both on their proximity to the forest and having a sufficient data record. Additionally, weather stations were selected that represented a variety of elevations and subsections (table 17). All of the stations, except the Entiat weather station, have a record of daily air temperatures of over 40 years with the Cle Elum and Stehekin stations having recorded data since 1931, a record of 71 years.

From the full data record, the average August maximum and minimum air temperatures were calculated for each year. (The month of August was chosen because air temperatures tend to peak then and in 2001 peak air and water temperatures occurred in mid-August.) Percentiles were then determined from the full record of annual average August maximum and minimum values. This information is presented in table 17 along with the average August maximum and minimum temperatures observed in 2001. (The 2001 data were compared to the historic record based on their percentile position. The 2001 percentile is included in table 17 in parentheses.)

As observed, August 2001 had above average maximum and minimum air temperatures. For Stehekin and Cle Elum, the average August 2001 maximum represented the 87th and 81st percentiles, respectively. (Both of these stations have over a 70 year data record.) Similarly, minimum August air temperatures were also above average in 2001 in comparison to the historic record. The 2001 August average minimum represented the 97th and 92nd percentile for Stehekin and Cle Elum, respectively. (A more elevated minimum air temperature has the effect of reducing the night-time cooling potential of surface waters.)

Table 17. Percentiles of average maximum and minimum (italics) air temperatures (oF) for the month of August observed at weather stations within proximity to the Wenatchee National Forest in comparison to those observed in 2001.

Weather Station	**Elevation (ft)**	**Period of Record**	**Max**	**Min**	**75th**	**25th**	**Median**	**2001**
Entiat	960	1989-Present	89.3 *55.5*	79.8 *47.7*	87.6 *54.2*	84.7 *52.1*	86.3 *53.4*	88.5 (92nd) *53.9 (60th)*
Chelan	1120	1958-Present	91.7 *64.1*	77.9 *51.5*	87.0 *61.3*	83.0 *57.6*	84.2 *59.4*	88.2 (83rd) *61.9 (85th)*
Stehekin	1270	1931-Present	89.9 *57.9*	73.5 *46.7*	83.4 *54.3*	78.5 *50.0*	81.3 *51.6*	85.8 (87th) *57.8 (97th)*
Cle Elum	1920	1931-Present	90.0 *55.3*	73.1 *44.8*	83.3 *51.3*	77.8 *47.6*	80.6 *49.9*	83.7 (81st) *53.0 (92nd)*
Stampede Pass	3958	1944-Present	75.1 *54.5*	56.6 *43.2*	67.0 *48.9*	62.0 *45.5*	64.4 *47.2*	66.6 (67th) *49.4 (81st)*

Discharge Analysis – Historic to 2001

Discharge levels during the 2001 summer period were at historic low levels. (The level of discharge is an important factor in determining a particular stream's susceptibility to heating.) For this reason, the summer of 2001 provides an excellent baseline for examining the extreme condition leading to conservative assumptions in the analysis process.

To provide some perspective between the flow levels observed in 2001 to those observed historically, the flow record of United States Geological Survey (USGS) gauging stations in proximity to the Wenatchee Forest were examined. Table 18 provides a list of these gauging stations and their period of record. Because typically the month of August is when the warmest water temperatures occur (and this was the case in 2001), an examination of the average annual August flow level for the period of record was made. Table 19 provides an overview of this analysis based on percentiles of average annual August flow levels covering the period of record.

As observed, for the streams with no diversions, American and Stehekin Rivers, the August 2001 flow levels were at the 12th percentile in comparison to historic average August flow levels. Stated another way, among the August flows that have been measured historically, and for American and Stehekin Rivers this is 66 and 80 years, respectively, 88% have been greater. For those streams with more diversions present, in-stream flows were lower. For the Wenatchee River at Monitor, the average August 2001 flow of 581 represented the 3rd percentile (97% of average August flows were greater). Flows in the Chiwawa River were less impacted by the unusually low precipitation conditions in 2000/2001 due to contributions from high elevation snow and glacial melt (figure 13).

Table 18. Background information on USGS gauging stations in proximity to the Wenatchee National Forest.

USGS Station	Station Number	Drainage Area (mi^2)	Period of Record	Diversion
Stehekin	12451000	321	1911-15, 1927-Present (n=80)	No known regulation or diversion
Chiwawa	12456500	170	1911-14, 1936-49, 1954-57, 1993-Present (n=30)	Single irrigation diversion (approx. 20 cfs)
Icicle	12458000	193	1936-71, 1993-Present (n=43)	Regulation in headwater lakes. No diversion
American (Nile)	12488500	79	1909-11, 1913-15, 1939-Present (n=66)	No known regulation or diversion
Entiat (Ardenvoir)	12452800	203	1957-Present (n=44)	Numerous diversions
Entiat (Entiat)	12452990	419	1996-Present (n=6)	Numerous diversions
Wenatchee (Monitor)	12462500	1301	1962-Present (n=39)	Numerous diversions
Wenatchee (Peshastin)	12459000	1000	1929-Present (n=72)	Numerous diversions

Table 19. Average August flow (cubic feet per second) percentiles for several USGS gauging stations covering the flow record along with levels observed in 2001.

Station	Maximum	75th Percentile	50th Percentile	25th Percentile	Minimum	8- 2001 Median (percentile)
Stehekin	2716	1397	1206	935	681	816 (12th)
Chiwawa	899	355	251	169	106	168 (25th)
Icicle	764	330	229	180	121	141 (8th)
American (Nile)	343	104	78	59	41	50 (12th)
Entiat (Ardenvoir)	577	261	188	139	99	107 (2nd)
Entiat (Entiat)	655	353	287	230	123	122 (-)
Wenatchee (Monitor)	3985	1822	1287	810	457	581 (3rd)
Wenatchee (Peshastin)	3969	1790	1301	944	675	712 (7th)

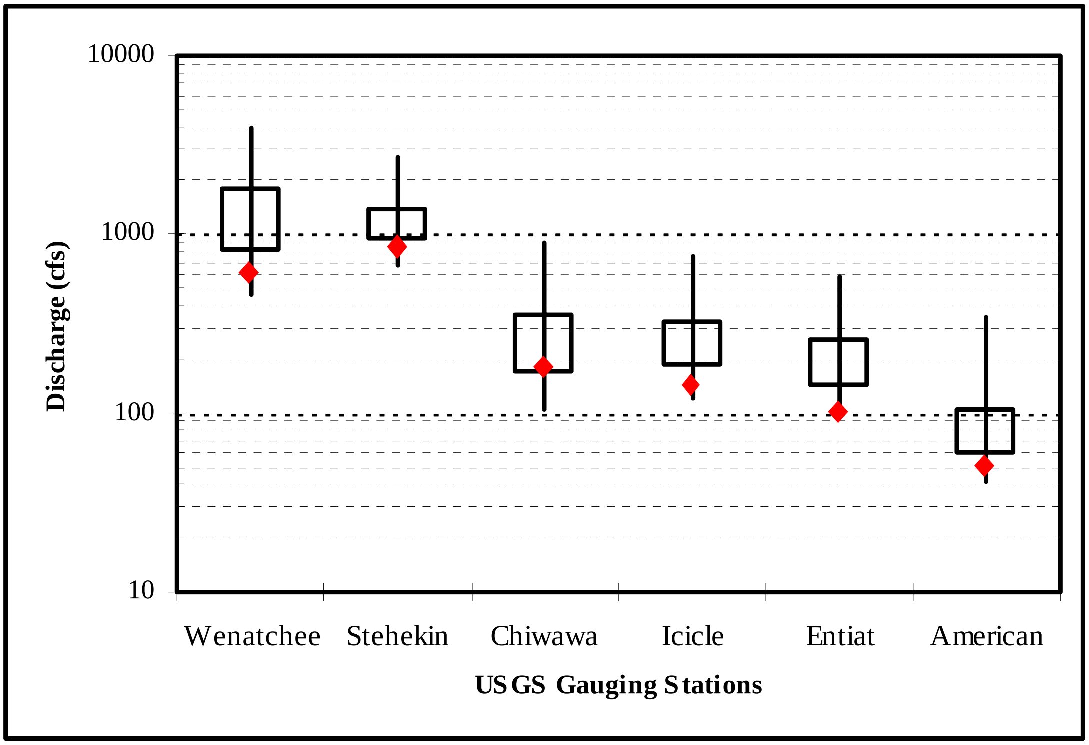

Figure 13. Box plots of average annual August flow levels (cfs) observed at USGS gauging stations in proximity to the Wenatchee National Forest for their respective period of record. (Red dots represent the median August flow for 2001. Endpoints on vertical lines represent the maximum and minimum flows. The top and bottom of boxes represent the 75th and 25th percentiles.)

Summary Implementation Strategy

Introduction: (Refer to page 1 of this document)

Overview

In practical application, the determination of load allocations and load capacities, the primary objectives of TMDLs, really only provide a bare framework, a target, to base implementation activities on. For this reason, this section summarizes the strategy of how the USFS and Ecology will work together, and the elements of that work, to ensure effective actions towards meeting the established targets and restoring compliance with the temperature standard.

It is anticipated that with the exercise of due care and protection, water quality standards for temperature should be met by 2045.

Implementation Plan Development

The USFS and Ecology are the two principal agencies involved in this TMDL and with its subsequent implementation and monitoring activities. Establishing this partnership is a joint memorandum of agreement signed in 2000. In addition, and crucial to the implementation of this TMDL, are current regulations under the Northwest Forest Plan regarding riparian vegetation throughout the Wenatchee National Forest.

The framework for the implementation of this TMDL is based on the Wenatchee National Forest Plan specifically the Aquatic Conservation Strategy, a major component of the plan that applies to all streams on National Forest System lands. Forest plan elements and associated riparian protection levels contained within the plan, serve as a benchmark for design of the TMDL assessments and are fundamental components of the TMDL implementation.

Reasonable Assurance

Assurance that allocations are met rely on regulations as they apply to riparian buffers contained within Wenatchee Land and Resource Management Plan, and the cooperative partnership between Ecology and the USFS.

<u>Ecology / USFS Memorandum of Agreement (MOA)</u>

This TMDL analysis is a cooperative effort between the Washington State Department of Ecology and the United States Forest Service. The partnership was formed through a 2000 memorandum of agreement (MOA). The initial impetus for the MOA was a joint recognition that inadequately maintained roads on USFS lands were resulting in significant water quality problems throughout the state. For this reason, the agreement established a schedule for planning and implementation of road maintenance and abandonment.

Importantly, in terms of this TMDL, is that the MOA also recognized the USFS as the Designated Management Agency for meeting Clean Water Act requirements on National Forest System lands and the Forest Service agreed to meet or exceed the water quality requirements in state and federal law. To meet this goal, the MOA recognized the necessity that the Forest Service and Ecology share responsibility for developing TMDLs on Forest System lands.

Ecology and the USFS meet annually to determine compliance with the MOA. These programs provide reasonable assurance for TMDL implementation and restoration of water quality for federal lands.

<u>United States Forest Service (USFS) – Northwest Forest Plan</u>

Forest plans are required by the National Forest Management Act (NFMA) for each National Forest. These plans establish land allocations, goals and objectives, and standards and guidelines used by land managers, other government agencies, private organizations, and individuals.

The Aquatic Conservation Strategy, a component of the forest plan, is designed to maintain and restore the ecological health and aquatic ecosystems. In general, watersheds that currently have the best habitat, or those with the greatest potential for recovery, are priority areas for increased protection and for restoration treatments. The conservation strategy aims to maintain the natural disturbance regime. Components of the Aquatic Conservation Strategy include:

Riparian Reserves: Lands along streams and unstable and potentially unstable areas where special standards and guidelines direct land use. Riparian reserves are designed to maintain and restore the ecological health and aquatic ecosystems. Interim widths for Riparian Reserves are established based on ecological and geomorphic factors. Interim Riparian Reserves for federal lands are delineated as part of the watershed analysis process based on identification and evaluation of critical hillslope, riparian, and channel processes. Final Riparian Reserve boundaries are determined at the site-specific level during the appropriate National Environmental Policy Act analysis.

Riparian Reserves are specified for categories of streams or water bodies as follows:

- Fish-bearing streams - Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of two site-potential trees, or 300 feet slope distance (600 feet total, including both sides of the stream channel), whichever is greatest.

- Permanently flowing non-fish bearing streams - Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of one site-potential tree, or 150 feet slope distance (300 feet total, including both sides of the stream channel), whichever is greatest.

- Specific riparian buffer zones ranging from 100 to 300 feet of slope distance are also specified for the following categories of riparian areas: constructed ponds and reservoirs, and wetlands; lakes and natural ponds; seasonally flowing or intermittent streams, wetlands less than one acre, and unstable and potentially unstable areas; wetlands and meadows less than one acre in size.

Key Watersheds: A system of refugia comprising watersheds crucial to at-risk fish species and stocks while also providing high quality water. Key Watersheds are generally those identified as watersheds as having the best habitat or those with the greatest potential for recovery are priority areas for increased protection and for restoration treatments. Activities to protect and restore aquatic habitat in Key Watersheds are a higher priority than similar activities in other watersheds.

Watershed Analysis: Procedures for conducting analysis that evaluates geomorphic and ecological processes operating in specific watersheds. This analysis should enable watershed planning that achieves Aquatic Conservation Strategy objectives. Watershed analysis provides the basis for monitoring and restoration programs and the foundation from which the Riparian Reserves can be delineated.

Watershed Restoration: A comprehensive, long-term program of watershed restoration to restore watershed health and aquatic ecosystems, including habitats supporting fish and other aquatic and riparian-dependent organisms.

A provision of the plan that provides further implementation assurance is that the USFS consults with the U.S. Environmental Protection Agency when there are revisions to the Forest Land and Resource Management Plan. These consultations will include any plan revisions that may affect TMDL implementation.

Additional implementation measures are being undertaken within the Wenatchee Forest through a roads analysis. The objective of the roads analysis is to identify a maintenance level for each road segment and any corrective measures needed to resolve water quality issues. This planning action is being accomplished with public and agency (federal and state) input.

Water Quality Restoration Plans are Forest Service planning documents that identify Best Management Practice actions appropriate to correct water quality issues within defined drainage areas. These plans will enhance and focus activities and improve shade levels in areas where the plans are developed.

Ecology staff will review USFS planning and implementation activities to ensure that state water quality laws and regulations are being met or exceeded. This includes the responsibility to certify that general water quality Best Management Practices (BMPs) and current Forest Plans are consistent with the CWA. The certification process includes the comparison of state BMPs and USFS BMPs. If Ecology or the USFS determines that USFS BMPs provide less resource protection than state BMPs, the USFS will review the BMPs for amendment.

Adaptive Management

Ecology will utilize its existing resources and authorities under RCW 90.48 to implement this TMDL. Working closely with the Forest Service, Ecology will set reasonable, achievable, and effective strategies for meeting the targets (load allocations) established in this TMDL and will include these activities in the Detailed Implementation Plan. If water quality standards for temperature are met without meeting the target load allocations then the objectives of this TMDL are met and no further Best Management Practices (BMPs) are needed. If the target load allocations are met, but the stream still does not meet water quality standards for temperature, then BMPs established in the Detailed Implementation Plan shall be made more stringent or revised. It is anticipated that the direction of implementation activities will allow for change based on new information or conditions.

If implementation activities are not producing expected or required results, Ecology may choose to conduct additional studies to identify the significant sources of heat input to the river system. If the causes can be determined, additional implementation measures may be needed. The USFS has a policy of adaptive management. Re-evaluation is anticipated to occur at five to ten year intervals and the TMDL may be modified as a result. Additional events that would require a review and subsequent TMDL revision, include: new Endangered Species Act listings, new water quality standards that apply to the Wenatchee Forest, or some unforeseen event affecting the landscape.

Monitoring Strategy

Following the approval of this TMDL by the United States Environmental Protection Agency, Ecology will develop, with assistance of the USFS, a Detailed Implementation Plan (DIP). The DIP will provide greater detail to all of the elements presented in this section (Strategic Implementation Strategy) and will contain a monitoring plan, used to evaluate implementation measures. The monitoring strategy will include the following measures: 1) the USFS will continue to monitor water temperatures throughout the forest annually (summer period) at established locations (compliance monitoring); 2) Ecology and USFS will review that information, along with other aspects of the TMDL implementation, at annual MOA meetings and; 3) effectiveness monitoring of shade levels by Ecology will occur within an appropriate timeframe.

Potential Funding Sources

The Wenatchee National Forest has funded restoration activities implemented on lands it administers. The types of restoration activities include road decommissioning, road stabilization and riparian plantings. The types of funds used to complete this work include Emergency Repair for Federally-Owned Roads, Supplemental Emergency Flood, and Appropriated funds.

References Cited

American Public Health Association. 1998. *Standard Methods for the Examination of Water and Wastewater, 20th Edition,* , Washington D.C

Amerman, K.S. and J.F. Orsborn. August 1987. *"An Analysis of Streamflows on the Olympic Peninsula in Washington State"*. Albrook Hydraulics Lab, Department of Civil and Environmental Engineering, Washington State University. Pullman, WA.

Bartholow, J.M. June 1989. *"Stream Temperature Investigations: Field and Analytic Methods"*. Instream Flow Information Paper No. 13. Biological Report 89(17). U.S. Fish and Wildlife Service. Fort Collins, CO.

Beschta, R.L. and J. Weatherred. 1984. *"TEMP-84: A Computer Model for Predicting Stream Temperatures Resulting from the Management of Streamside Vegetation"*. Watershed Systems Development Group. USDA Forest Service. Report WSDG-AD-00009. 76 pp.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. *"Stream Temperature and Aquatic Habitat: Fisheries and Forests Interactions"*. Ed. E.O. Salo and T.W. Cundy -- Proceedings of a symposium held February 1986, University of Washington. Seattle, WA: 1991-232.

Beschta, R.L. and R.L. Taylor. 1988. *"Stream Temperature Increases and Land Use in a Forested Oregon Watershed"*. Water Resources Bulletin 24(1): 19-25.

Bicknell, B.R., J.C. Imhoff, J. Kittle, A.S. Donigian, and R.C. Johansen. September 1996. *"Hydrological Simulation Program – FORTRAN, User's Manual for Release 11"*. U.S. Environmental Protection Agency, Environmental Research Laboratory. Athens, GA.

Boyd, M.S. 1996. *"Heat Source©: Stream, River, and Open Channel Temperature Prediction"*. Master's Thesis. Oregon State University. Corvallis, OR.

Bowie, G.L., W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W.H. Chan, S.A. Gherini, and C.E. Chamberlin. June 1985. *"Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition)"*. U.S. Environmental Protection Agency, Environmental Research Laboratory. EPA/600/3-85/040. Athens, GA.

Bowen, I.S. 1926. *"The Ratio of Heat Losses by Convection and Evaporation From Any Water Surface"*. Physical Review. Series 2, Vol 27: 779-787.

Brazier, J.R. and G.W. Brown. 1973. *"Buffer Strips for Stream Temperature Control"*. Research Paper 15. Forest Research Laboratory, School of Forestry, Oregon State University. Corvallis, OR.

Brown, G.W. 1969. *"Predicting Temperatures of Small Streams"*. Water Resources Research. 5(1): 68-75.

Brown. G.W. 1970. *"Predicting the Effects of Clearcutting on Stream Temperatures"*. Journal of Soil and Water Conservation. 25: 11-13.

Brown, G.W. and J.T. Krygier. 1970. *"Effects of Clear Cutting on Stream Temperatures"*. Water Resources Research. 6(4): 1133-1140.

Brown, G.W. 1971. *"An Improved Temperature Prediction Model for Small Streams"*. Research Report WRRI-16. 20pp. Water Resource Research Institute. Oregon State University. Corvallis, OR.

Brown, L.C. and T.O. Barnwell. May 1987. *"The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual"*. U.S. Environmental Protection Agency, Environmental Research Laboratory. EPA/600/3-87/007. Athens, GA.

Chen, Y.D. 1996. *"Hydrologic and Water Quality Modeling for Aquatic Ecosystem Protection and Restoration in Forest Watersheds: A Case Study of Stream Temperature in the Upper Grande Ronde River, Oregon"*. Ph.D. Dissertation. University of Georgia. Athens, GA.

Chen, J., Saunders, S.C., Crow, T.R., Naiman, R. J., Brosofske, K.D., Mroz, G.D., Brookshire, B.L., and Franklin, J.F.. 1999. Microclimate in forest ecosystem and landscape ecology. *BioScience*. 49:4, 288-297.

Davis, Carl. 1994. Wenatchee National Forest: Subsections. United States Department of Agriculture, United States Forest Service.

Dong, J., Chen, J., Brosofske, and Naiman, R.J.. 1998. Modeling air temperature gradients across managed small streams in western Washington. *Journal of Environmental Management*. 53, 309-321.

Donigian, A.S., Jr., and N.H. Crawford. 1976. *"Modeling Nonpoint Pollution from the Land Surface"*. U.S. Environmental Protection Agency. EPA 600/3-76-083. Athens, GA.

Edinger, J.E., Brady, D.K. and Geyer, J.C. 1974. *Heat Exchange and Transport in the Environment*. EPRI Publication No. 74-049-00-3, Electric Power Research Institute, Palo Alto, CA.

Gebhardt, K. And H. Fisher. 1998. *"Using Surrogates for Nonpoint Source Water Quality Loading Allocation: Part 1. Stream Temperature"*.

Gibbons, D.R. and E.O. Salo. 1983. *"An Annotated Bibliography of the Effects of Logging on Fish of the Western United States and Canada"*. USDA Forest Service General Technical Report PNW-10. 145 pp. Pacific Northwest Forest and Range Experiment Station. Portland, OR.

Ibqal, M. 1983. *"An Introduction to Solar Radiation"*. 213 pp. Academic Press. New York, NY.

Jobson, H.E. and T.N. Keefer. 1979. *"Modeling Highly Transient Flow, Mass, and heat Transfer in the Chattahoochee River near Atlanta, Georgia"*. Geological Survey Professional Paper 1136. U.S. Government printing Office, Washington, DC.

Lafferty, B. 1987. *"A Procedure for Evaluating Buffer Strips for Stream Temperature Protection under the Forest Practices Act"*. pp. 70 - 77 in Managing Oregon's Riparian Zone for Timber, Fish, and Wildlife. NCASI Technical Bulletin No. 514. 96 pp.

Ledwith, T. 1996. *Effects of buffer strip width on air temperature and relative humidity in a stream riparian zone*. Thesis, Humboldt State University, Arcata, CA**.**

Lillybridge, Terry, Bernard Kovalchik, Clinton Williams, Bradley Smith. 1995. Field Guide for Forested Plant Associations of the Wenatchee National Forest. General Tech. Rpt. PNW-GTR-359.

Lynch, J.A. 1985. Best management practices for controlling nonpoint source pollution on forested watersheds. *Journal of Soil and Water Conservation* 40, 164-167.

McCutcheon, S.C. 1989. *"Water Quality Modeling: Volume 1, Transport and Surface Exchange in Rivers"*. pp. 183 - 209. CRC Press, Boca Raton, LA.

McElroy, A.D., S.Y. Chiu, J.W. Nebgen, A. Aleti, and F.W. Bennett. 1976. *"Loading Functions for Assessment of Water Pollution from Nonpoint Sources"*. U.S. Environmental Protection Agency. EPA 600/2-76-151. Washington, D.C.

McNab, H.W. and P.E. Avers. 1994. *Ecological Subregions of the United States – Section Descriptions*. USDA Forest Service. WO-WSA-5.

Meehan, W.R., W.A. Farr, D.M. Bishop , and J.H. Patric. 1969. *"Some Effects of Clearcutting on Salmon Habitat of Two Southeast Alaska Streams"*. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Paper PNW-82. 45 pp.

Mills, W.B., D.B. Porcella, M.J. Ungs, S.A. Gherini, K.V. Summers, L. Mok, G.L. Rupp, G.L. Bowie, and D.A. Haith. September 1985. *"Water Quality Assessment: A Screening Procedure for Toxic and Conventional Pollutants in Surface and Ground Water – Part I"* (Revised – 1985). U.S. Environmental Protection Agency, Environmental Research Laboratory. EPA/600/6-85/002a. Athens, GA.

National Advisory Council for Environmental Policy and Technology. July 1998. *"Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program"*. U.S. Environmental Protection Agency, Office of the Administrator. EPA-100-R-98-006. Washington, DC.

Parker, F.L. and Krenkel, P.A. 1969. *“Thermal Pollution: Status of the Art”*. Report 3. Vanderbilt University Department of Environmental and Resources Engineering. Nashville, TN.

Paulson, K. 1997. *“Estimating Changes in Sediment Supply Due to Forest Practices: A Sediment Budget Approach Applied to the Skagit River Basin in Northwestern Washington”*. 156 pp. M.S. Thesis. University of Washington. Seattle, WA.

Rashin, E. and C. Graber. 1992. Effectiveness of Washington's Forest Practice Riparian Management Zone Regulations for Protection of Stream Temperature. Publication No. 92-64. Washington Department of Ecology, Olympia. WA.

Reid, L.M. and T. Dunne. 1996. *“Rapid Evaluation of Sediment Budgets”*. CATENA VERLAG GMBH, 35447. Reiskirchen, Germany.

Rosgen, D.L.. 1996. *“Applied River Morphology”*. Wildland Hydrology. Pagosa Springs, CO.

Shanahan, P. January 1985. *“Water Temperature Modeling: A Practical Guide”*. Ed. T.O. Barnwell in Proceedings of Stormwater and Water Quality Model Users Group Meeting April 12-13, 1984. U.S. Environmental Protection Agency, Environmental Research Laboratory. EPA-600/9-85-003. Athens, GA.

Simpson Timber Company Northwest Operations. September 1999. Draft Habitat Conservation Plan.

Sinokrot, B.A. and H.G. Stefan. 1993. *“Stream Temperature Dynamics: Measurement and Modeling”*. Water Resources Research. 29(7): 2299-2312.

Theurer, F., K. Voos, and W. Miller. September 1984. *“Instream Water Temperature Model”*. Instream Flow Information Paper No. 16. U.S. Fish & Wildlife Service. U.S. Soil Conservation Service. FWS/OBS-84-15. Washington, D.C.

USDA Forest Service. February 1993. *“SHADOW: Stream Temperature Management Program User’s Manual Version 2.3"*. Pacific Northwest Region. Portland, OR.

USDA Forest Service – Mt. Baker / Snoqualmie National Forest. *“South Fork Snoqualmie Watershed Analysis”*.

USDA Forest Service – Siskiyou National Forest, Oregon Department of Environmental Quality. March 1999. *“Water Quality Management Plan – Sucker / Grayback Watershed”*.

U.S. Environmental Protection Agency. 1991. *“Guidance for Water Quality-based Decisions: The TMDL Process”*. EPA 440/4-91-001.

U.S. Environmental Protection Agency. March 1999. *“Redwood Creek Sediment TMDL”*. EPA Region 9. San Francisco, CA.

U.S. Environmental Protection Agency. March 1999. *"South Fork Trinity TMDL"*. EPA Region 9. San Francisco, CA.

Washington State Forest Practices Board. November 1995. *"Standard Methodology for Conducting Watershed Analysis: Version 3.0"*. Olympia, WA.

Washington State Forest Practices Board. March 1997. *"Standard Methodology for Conducting Watershed Analysis -- Water Quality Module: Version 1.0"*. Olympia, WA.

Wetzel, R.G. 1983. *"Limnology"*. pp 10. 2nd Edition. Saunders College Publishing. Philadelphia, PA.

Weyerhaueser, Simpson Timber Company. November 1995. *"West Fork Satsop Watershed Analysis"*.

Wunderlich, W.O. 1972. *"Heat and Mass Transfer Between a Water Surface and the Atmosphere"*. pp 4 - 20. Water Resources Research Laboratory Report No. 14. Tennessee Valley Authority. Norris, TN.

Appendix A
Public Involvement

Appendix B
Monitoring Data

Station Name	Stream Name	Basin	Elevation (ft)	Drainage Area (acres)	Effective Shade (%)	Max. Temperature August 12th °F
DEEP_01	Deep	Naches	3498	15271	62	49.1
GOLD_02	Gold	Chelan	2976			52.0
NF25_01	NF Twenty-five	Chelan	1876	12512	74	52.3
TIMB_01	Timber	Naches	3576	1832	97	52.9
WFIR_01	West Fork Iron	Yakima	3074	809	57	52.9
KETT_01	Kettle	Naches	3356	3926	96	53.3
JACK_01	Jack	Yakima	3127	2372	89	53.8
MARB_01	Marble	Wenatchee	2470	2558	96	54.1
FALL_01	Fall	Entiat	4161	3114	67	54.2
SAFE_02	Safety	Chelan	4025	5470	34	54.6
UNIO_01	Union	Naches	3401	7256	89	54.6
FORT_01	Fortune	Yakima	3221	6379	35	54.8
WFQU_01	West Fork Quartz	Naches	3205	2746	82	54.9
COYO_01	Coyote	Chelan	4046	667	40	55.0
INDIT_01	Indian	Naches	2958	12658		55.0
RANI_01	Rainier Fork	Naches	3853	4631	98	55.1
PHEL_02	Phelps	Wenatchee	3525	9464		55.2
POIS_01	Poison	Chelan	3150	3774	30	55.2
FIRS_01	First	Chelan	1205	11621	54	55.4
ENTI_16	Entiat River	Entiat	3097	34684	47	56.0
SF25_01	SF Twenty-five	Chelan	1903	11102	56	56.1
BLOW_01	Blow	Naches	3366	2776	82	56.2
THOR_01	Thorp	Yakima	3241	2938	25	56.3
BEAV_01	Beaver	Wenatchee	2395	3323	74	56.6
INDIE_01	Indian	Entiat	2045	3677	58	56.7
MINN_01	Minnow	Wenatchee	2462	2008	82	56.9
WFBE_01	West Fork Bear	Naches	3377	3256		56.9
AMER_05	American River	Naches	3655	4993		57.5
MADR_06	Mad River	Entiat	3359	14260		57.6
COUG_01	Cougar	Entiat	3365	8351	56	58.0
FRCA_01	French Cabin	Yakima	3153	4496	48	58.0
MADR_07	Mad River	Entiat	4576	6333		58.0
PILE_01	Pileup	Naches	2877	5579	92	58.0
TILL_01	Tillicum	Entiat	1420	14566	35	58.0
PHEL_01	Phelps	Wenatchee	2809	11407	41	58.2
LTRA_03	Little Rattlesnake	Naches	3667	7268	78	58.3
BEAR_02	Bear	Naches	3170	3640		58.7
BEAV_02	Beaver	Wenatchee	2387	1059	81	58.7
CHWA_04	Chiwawa	Wenatchee	2465	43605		58.7
ENTI_15	Entiat	Entiat	2659	47786	55	58.7
LAKEE_01	Lake	Entiat	2289	8934	60	58.8
NFLN_01	NF Little Naches	Naches	3253	11940	71	58.8
SFTI_03	SF Tieton	Naches	3950	16240		58.8
MUDD_01	Mud	Entiat	1701	14385		59.0
CHWA_05	Chiwawa	Wenatchee	2781	15753		59.1

AMER_04	American River	Naches	3630	12281		59.2
RAIN_01	Rainy	Wenatchee	2159	10862		59.2
SFLN_01	SF Little Naches	Naches	3080	9711	83	59.2
WHIT_02	White	Wenatchee	1877	95842		59.2
QUAR_01	Quartz	Naches	2706	10364	64	59.3
CHWA_03	Chiwawa	Wenatchee	2415	62946		59.4
CROW_02	Crow	Naches	3217	18759	60	59.4
MATH_01	Mathew	Naches	3087	2069	88	59.4
MFLN_01	MF Little Naches	Naches	3363	4560	88	59.4
BOXC_01	Box Canyon	Yakima	2273	7743	85	59.9
PINE_01	Pine	Naches	2535	1544		59.9
WHIT_01	White	Wenatchee	1869	73809	26	60.0
CHIW_01	Chiwaukum	Wenatchee	1768	25830	53	60.3
MEAD_01	Meadow	Yakima	2527	5395	46	60.3
GRAD_02	Grade	Entiat	3484	5513	73	60.5
MADR_05	Mad River	Entiat	2912	27826		60.5
ROCK_01	Rock	Wenatchee	2504	13817	40	60.5
BEAR_01	Bear	Naches	3133	7700		60.7
NFEN_01	NF Entiat	Entiat	2680	17653	62	60.7
WHIT_04	White	Wenatchee	2378	26258		60.8
WHIT_03	White	Wenatchee	2302	42614		60.8
CHIK_01	Chikamin	Wenatchee	2407	13943	59	61.1
MITC_01	Mitchel	Chelan	2632	4045	30	61.2
CROW_01	Crow	Naches	2756			61.4
ENTI_14	Entiat River	Entiat	2372	91998	38	61.7
BLUE_01	Blue	Yakima	2833	2294	80	61.8
LTWE_09	Little Wenatchee	Wenatchee	2935	6961	52	62.3
PESH_01	Peshastin	Wenatchee	1801	61957		62.4
SANDN_01	Sand	Naches	2918	4107		62.5
GREY_01	Grey	Naches	3401			62.7
JUNGY_01	Jungle	Yakima	2617	3924	38	62.8
NFTA_01	NF Taneum	Yakima	2818	15293	60	62.8
SANDW_01	Sand	Wenatchee	1426	11941	24	63.1
SFTI_01	SF Tieton	Naches	3015			63.1
TWEN_01	Twenty	Chelan	1219	26611		63.4
LTRA_02	Little Rattlesnake	Naches	3104	11239	71	63.8
PRES_01	Preston	Entiat	1735	4645	30	63.8
LAKEW_01	Lake	Wenatchee	2333	11014	51	63.9
LTRA_01	Little Rattlesnake	Naches	2100	16228	44	63.9
STAF_01	Stafford	Yakima	2795	14240	44	63.9
STOR_01	Stormy	Entiat	1579	5435	23	63.9
CABI_03	Cabin	Yakima	2910			64.0
IRON_01	Iron	Yakima	2944	3876	60	64.1
HAUS_01	Hause	Naches	2716	2224		64.4
LTWE_07	Little Wenatchee	Wenatchee	2431	21138		64.4
LTNA_06	Little Naches	Naches	3135	18835		64.8
BUMP_06	Bumping River	Naches	3474	16541		64.9
CHWA_02	Chiwawa	Wenatchee	2084	110566		64.9
LTNA_05	Little Naches	Naches	3103	27323		64.9
ENTI_13	Entiat	Entiat	1737	102845	22	65.1

LTWE_03	Little Wenatchee	Wenatchee	1954	55011		65.2
ROAR_02	Roaring	Entiat	1546	13449		65.3
LTWE_05	Little Wenatchee	Wenatchee	2117	41337		65.9
MINE_01	Mineral	Yakima	2482	3656	66	66.2
PESH_02	Peshstin	Wenatchee	1813	38328	37	66.2
POTA_01	Potato	Entiat	1576	6587	38	66.5
LTWE_01	Little Wenatchee	Wenatchee	1877	65001		66.6
ICIC_01	Icicle	Wenatchee	1246	131408	38	66.7
LTNA_04	Little Naches	Naches	2930	40744		66.7
ENTI_12	Entiat River	Entiat	1690	109646	18	67.2
MFTE_01	MF Tenaway	Yakima	2656	16554	39	67.4
LTWE_02	Little Wenatchee	Wenatchee	1912	60722		67.5
CLEE_01	Cle Elum	Yakima	1975	141996		67.8
DEVI_01	Devils Gulch	Wenatchee	1772	10399	33	67.8
MADR_03	Mad River	Entiat	1834	32999		67.8
WAPT_01	Waptus	Yakima	2508	33814	48	68.1
LTNA_02	Little Naches	Naches	2716	59047		68.4
TANE_01	Taneum	Yakima	2720	31563		68.5
MADR_04	Mad River	Entiat	2440	31050		68.6
ENTI_11	Entiat	Entiat	1614	119949		68.9
COOP_01	Cooper	Yakima	2360	23862	46	69.2
MILL_01	Mill	Entiat	1107	7328	12	69.2
MADR_O2	Mad River	Entiat	1668	40378		69.3
YAKI_01	Yakima	Wenatchee	2200	52936		69.3
ENTI_09	Entiat River	Entiat	1462	141123		69.7
LTNA_01	Little Naches	Naches	2547	95540		69.8
BUMP_01	Bumping River	Naches	2560	124378		69.9
MADR_00	Mad River	Entiat	1262	58440		70.0
MADR_01	Mad River	Entiat	1400	56760		70.1
ROAR_01	Roaring	Entiat	1248	15827	22	70.1
BUMP_03	Bumping River	Naches	2756	71019		70.8
EFMI_01	EF Mission	Wenatchee	1749	13046	25	71.4
PESH_03	Peshastin	Wenatchee	2156	34208		72.0
NASO_01	Nason	Wenatchee	1866	68162	34	72.2
SWAKE_01	Swakane	Entiat	1491	8666	26	73.9
ENTI_07	Entiat River	Entiat	1279	160582		74.0
ENTI_03	Entiat River	Entiat	931	250741		74.2
ENTI_06	Entiat River	Entiat	1225	219022		74.2
ENTI_05	Entiat River	Entiat	1107	224426		74.4
ENTI_01	Entiat River	Entiat	782	267646		75.5
ENTI_02	Entiat River	Entiat	857	254212		75.8